Asymmetric Reheating of Dark QED
Thermalization and Relics of a Hidden Sector

Simon Cléry, TUM

COSMO-26 - 29th International Conference on Particle Physics & Cosmology

Based on

- ✦ *Asymmetric Reheating of Dark QED*, SC, Kimus, Tytgat, **2605.09686**

See also

- ✦ *Light from darkness: History of a hot Dark Sector,* Coy, Kimus, Tytgat, **2405.10792**
- ✦ *The Domain of Thermal Dark Matter candidates,* Coy, Hambye, Tytgat, Vanderheyden, **2105.01263**
- ✦ *Thermalization after/during Reheating,* Harigaya, Mukaida, **1312.3097**

Technische Universität München

SFB 1258 Neutrinos Dark Matter Messengers

UNTERSTÜTZT VON / SUPPORTED BY Alexander von HUMBOLDT STIFTUNG

Hidden Sector Dark Matter

Standard thermal scenario: DM thermalized with SM bath and relic from non-relativistic Freeze-out

$$\Omega_\chi h^2 \simeq \frac{10^9}{\langle \sigma v \rangle m_{\rm Pl} \mathrm{GeV}} \to \langle \sigma v \rangle \sim 10^{-9} \mathrm{GeV}^{-2}$$

➜ WIMP miracle. But no WIMP detected so far…
Several ways to relax this constraint (Freeze-in, SIMP, Light and ULDM, etc…)

➜ One alternative: DM part of a broader **Hidden Sector (HS)**

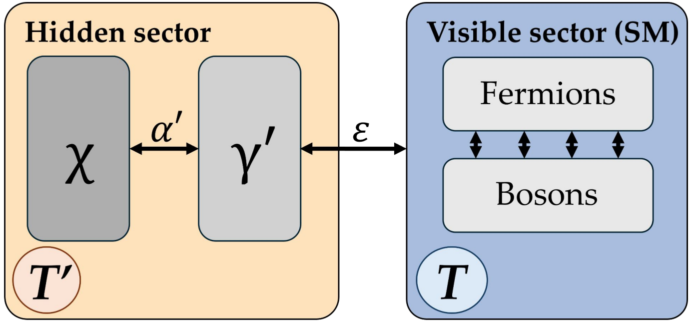
HS thermalized at $T' \neq T$ secluded from Visible Sector (VS) or with small HS-VS coupling **$\varepsilon \ll 1$**

DM relic from freeze-out of the HS

$$\Omega_\chi h^2 \simeq \frac{10^9 \times (T'/T)}{\langle \sigma v \rangle m_{\rm Pl} \mathrm{GeV}} \frac{s_{fo} a_{\rm fo}^3}{s_{\rm f} a_{\rm f}^3} \quad (T' \ll T)$$

Berlin, Hooper, Krnjaic, **1602.08490**

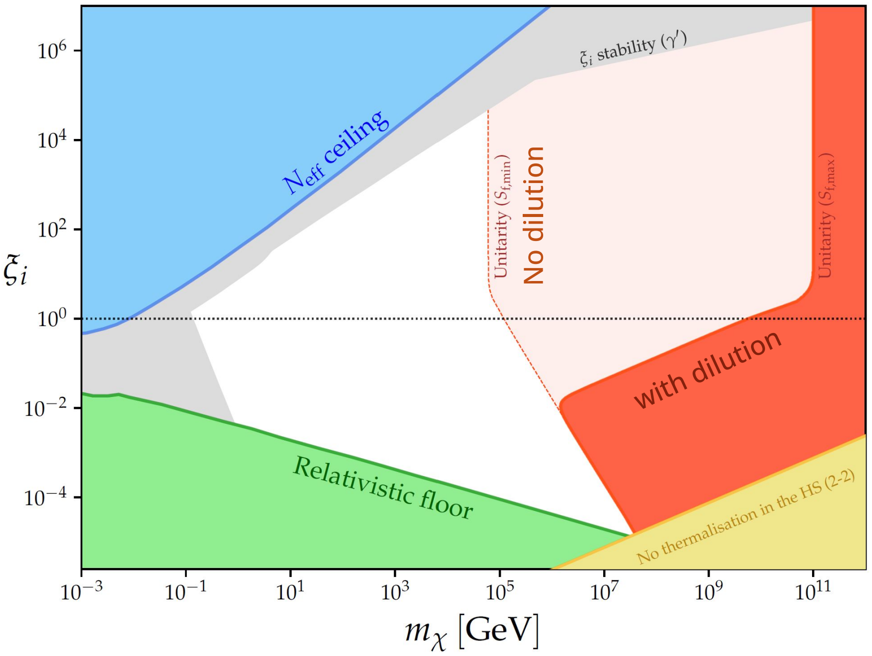
➜ **Broader parameter space**



$$\boxed{\xi \equiv \frac{T'}{T}}$$

Thermal Hidden Sector Dark Matter domain

- **Relativistic floor :** relativistic freeze-out yields the maximal relic abundance at fixed ξ = **T'/T** ➜ DM is under abundant
- **Neff ceiling :** DM particles are relativistic at BBN ➜ Lower bound on DM mass depending on ratio ξ = **T'/T** at freeze-out
- **ξ stability :** DM freeze-out from a secluded HS, with constant ξ
- **HS thermalization :** Efficient HS thermalization
- **Unitarity wall :** maximal cross section allowed by unitarity ➜ DM is over abundant



Light from darkness: History of a hot Dark Sector, Coy, Kimus, Tytgat, **2405.10792**

The Domain of Thermal Dark Matter candidates, Coy, Hambye, Tytgat, Vanderheyden, **2105.01263**

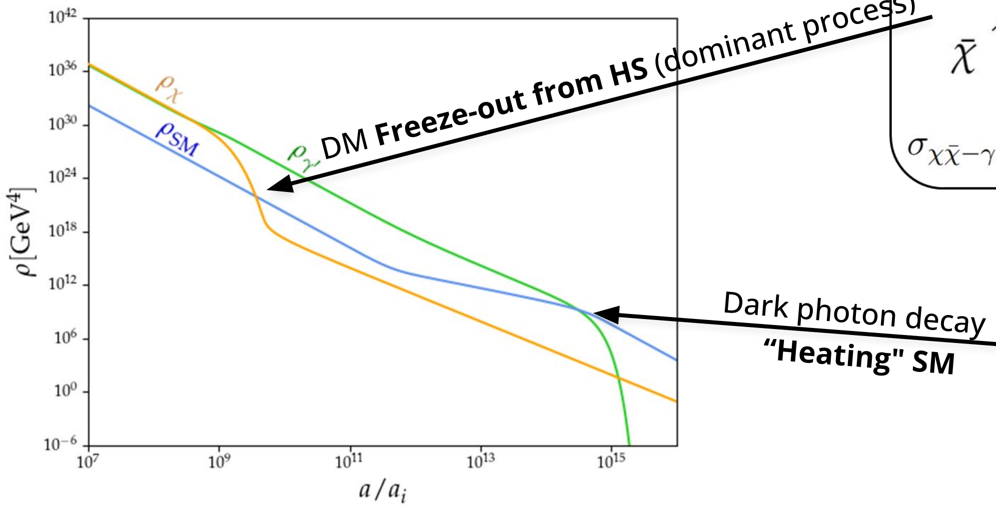
Dark QED

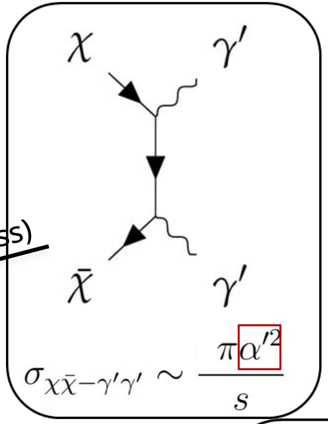
Benchmark model for the Hidden Sector $\mathcal{L} \supset \overline{\chi}\,(i\not{D} - m_\chi)\,\chi - \frac{1}{4}F'^{\mu\nu}F'_{\mu\nu} + \frac{1}{2}m^2_{\gamma'}A'_\mu A'^\mu - \frac{\varepsilon}{2}B_{\mu\nu}F'^{\mu\nu}$

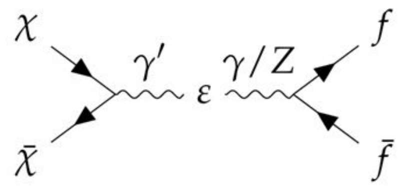
➜ Two Beyond SM fields:

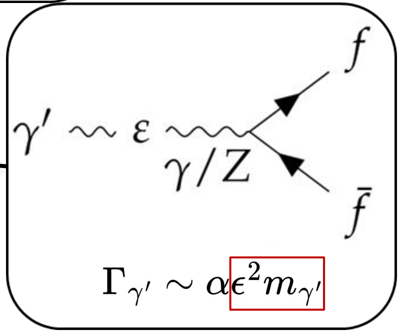
- ✦ ***Dark electron χ*** : DM
- ✦ ***Dark photon γ’*** : abelian gauge boson companion

➜ a mechanism to give a mass $m_{\gamma'}$ to dark photons
➜ small kinetic mixing **ε ≪ 1** between HS-VS

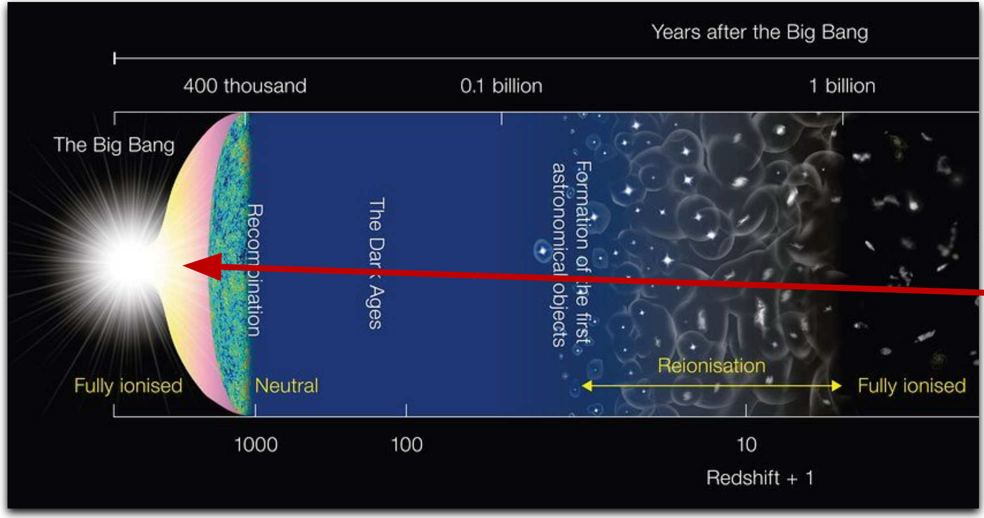


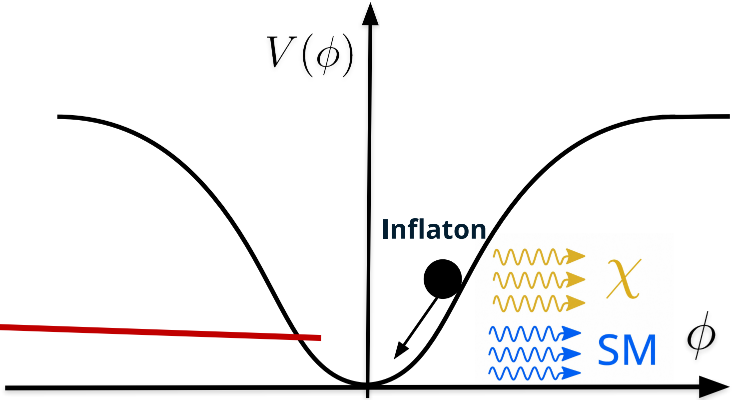






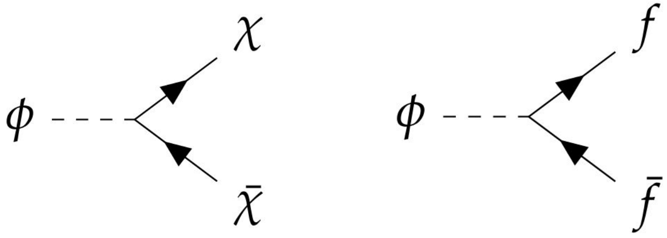
Asymmetric Reheating





Starobinsky-like inflation

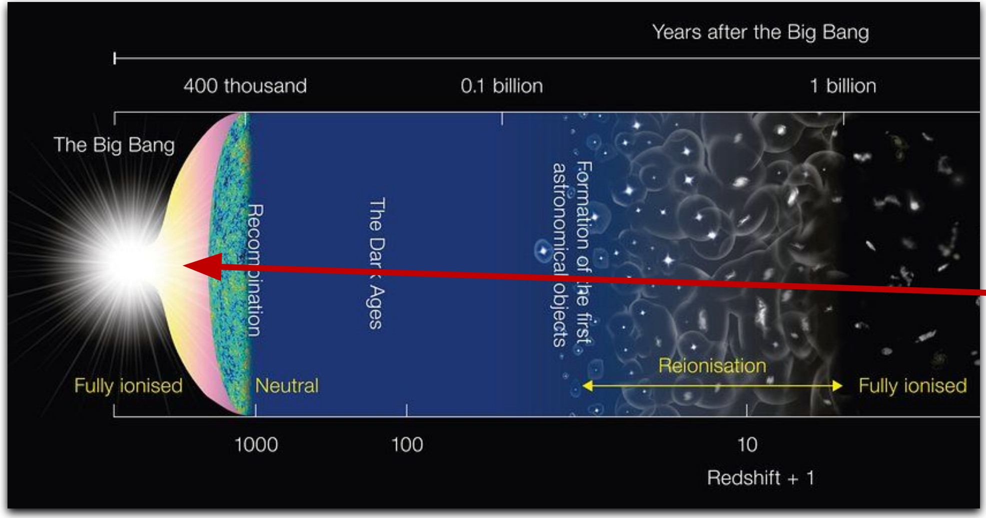
$$V(\phi) \approx \frac{1}{2} m_\phi^2 \phi^2 \qquad \boxed{m_\phi \simeq 3 \times 10^{13} \text{ GeV}}$$

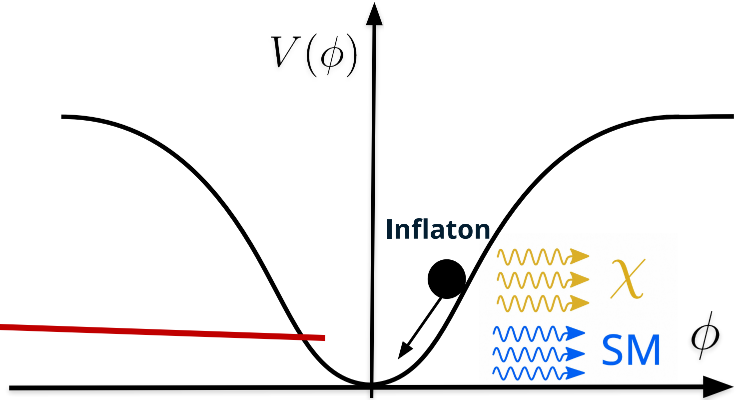


$$\Gamma_\phi^\chi \neq \Gamma_\phi^{\text{SM}}$$

What if inflaton is also coupled to the Hidden Sector ?
➜ **Asymmetric Reheating**

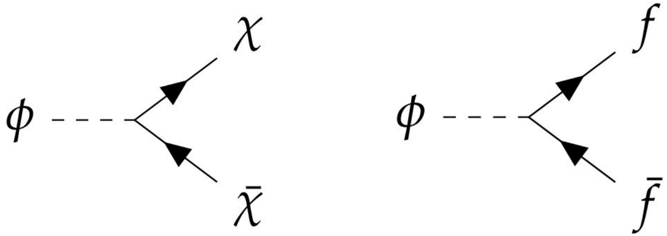
Asymmetric Reheating





Starobinsky-like inflation

$$V(\phi) \approx \frac{1}{2} m_\phi^2 \phi^2 \qquad \boxed{m_\phi \simeq 3 \times 10^{13}\ \mathrm{GeV}}$$



$$\Gamma_\phi^\chi \neq \Gamma_\phi^{\mathrm{SM}}$$

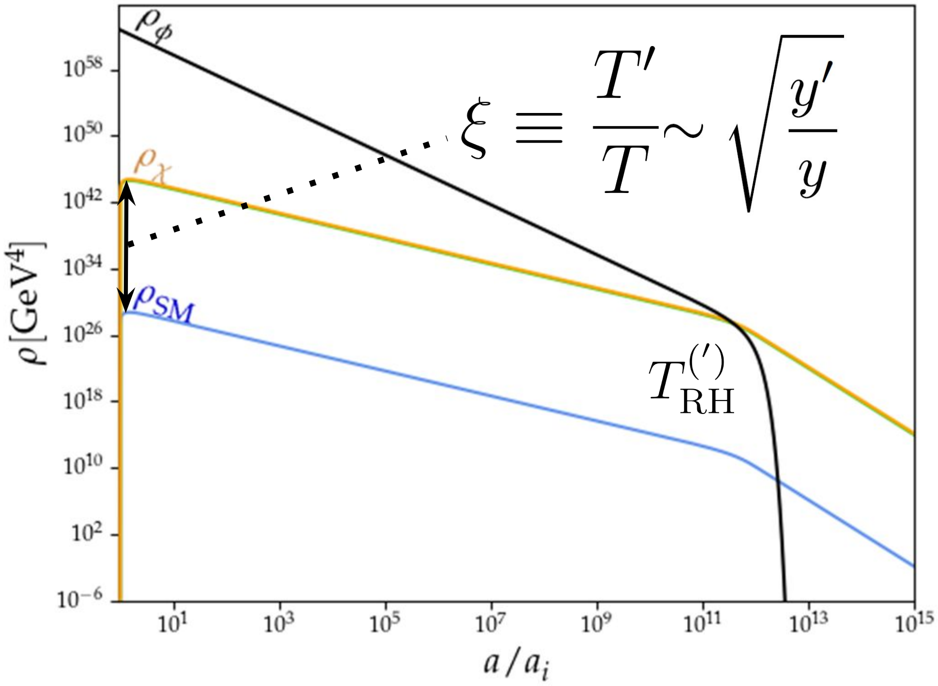
What if inflaton is also coupled to the Hidden Sector ?
➜ **Asymmetric Reheating**

$$\mathcal{L} \supset \frac{1}{2}\partial_\mu \phi \partial^\mu \phi - V(\phi) - y\phi \bar{f} f - y' \phi \bar{\chi} \chi$$

Asymmetric Reheating

Boltzmann equations

$$\begin{cases} \dot{\rho}_\phi + 3H\rho_\phi & = -\Gamma_\phi \rho_\phi \\ \dot{\rho}_\chi + 4H\rho_\chi & = \Gamma_\phi^\chi \rho_\phi \\ \dot{\rho}_{\rm SM} + 4H\rho_{\rm SM} & = \Gamma_\phi^{\rm SM} \rho_\phi \end{cases}$$



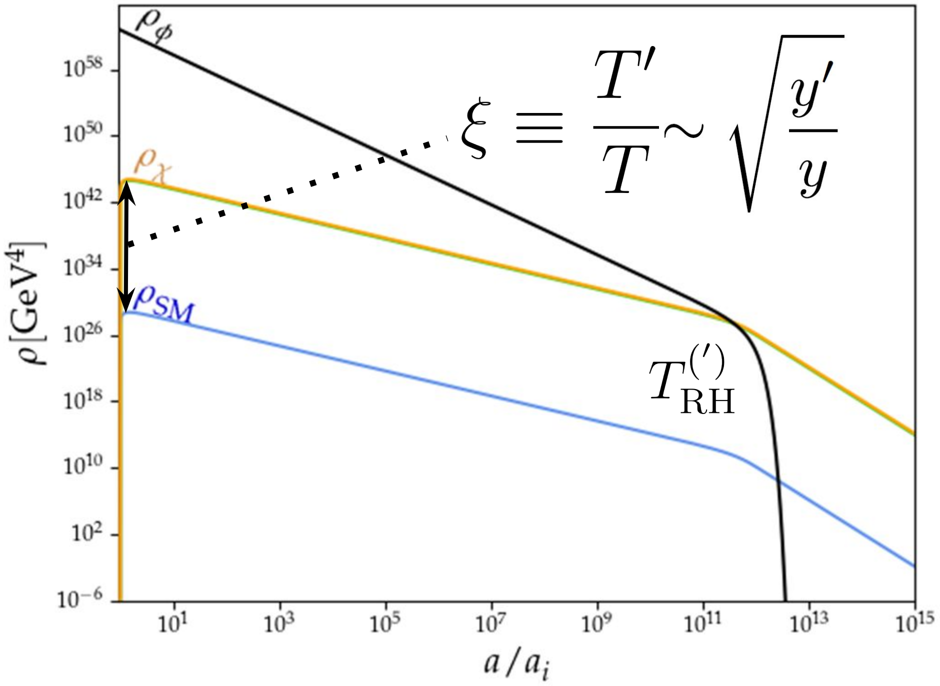
Asymmetric Reheating

Boltzmann equations

$$\begin{cases} \dot{\rho}_\phi + 3H\rho_\phi & = -\Gamma_\phi \rho_\phi \\ \dot{\rho}_\chi + 4H\rho_\chi & = \Gamma_\phi^\chi \rho_\phi \\ \dot{\rho}_{\mathrm{SM}} + 4H\rho_{\mathrm{SM}} & = \Gamma_\phi^{\mathrm{SM}} \rho_\phi \end{cases}$$

Assume rapid thermalization in the SM sector

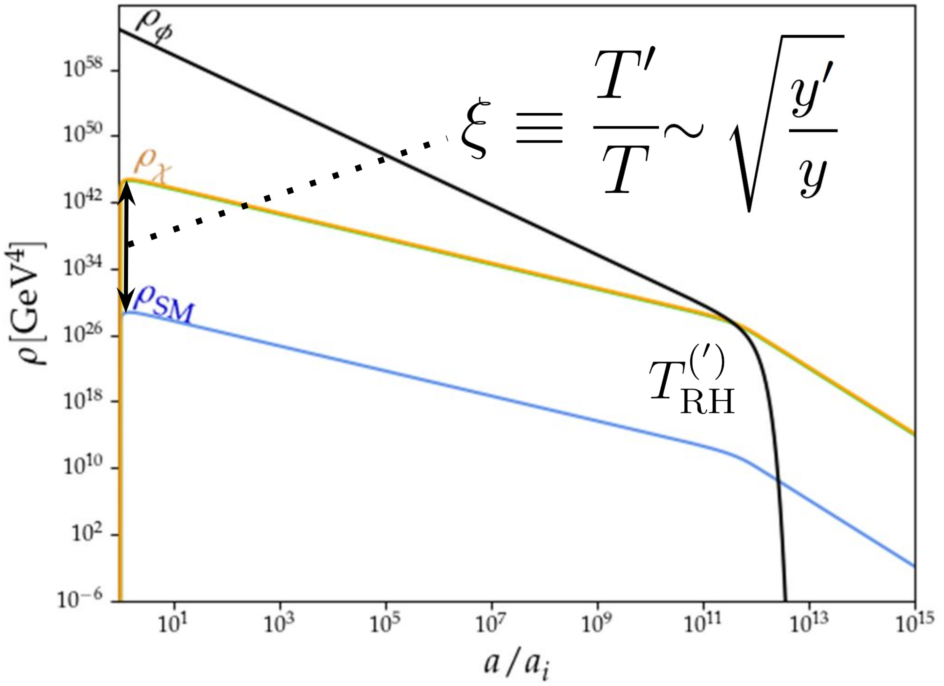
(large non-abelian gauge couplings, many degrees of freedom)



Asymmetric Reheating

Boltzmann equations

$$\begin{cases} \dot{\rho}_\phi + 3H\rho_\phi & = -\Gamma_\phi \rho_\phi \\ \dot{\rho}_\chi + 4H\rho_\chi & = \Gamma_\phi^\chi \rho_\phi \\ \dot{\rho}_{\rm SM} + 4H\rho_{\rm SM} & = \Gamma_\phi^{\rm SM} \rho_\phi \end{cases}$$



Assume rapid thermalization in the SM sector

(large non-abelian gauge couplings, many degrees of freedom)

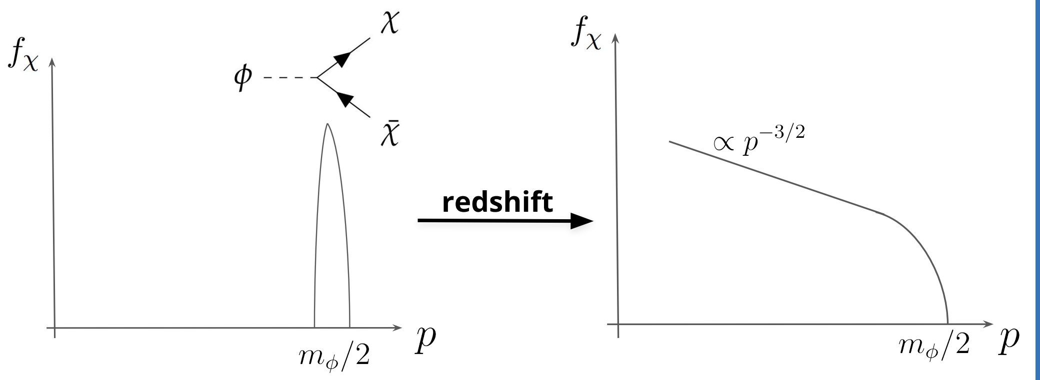
- ✦ **Thermalization of the HS ?**
- ✦ **Evolution of the temperature ratio ?**

Non-thermal, under abundant HS from inflaton decays

Inflaton decays inject a **hard, non-thermal population**

$$f_\chi \simeq 24\pi^2 \frac{n_\chi}{m_\phi^3}\left(\frac{m_\phi}{2p}\right)^{3/2}\Theta(m_\phi/2 - p)$$

Harigaya, Mukaida, **1312.3097**
Garcia, Amin, **1806.01865**



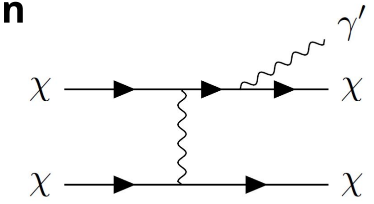
Typical momentum $\langle p \rangle \sim O(m_\phi)$

Underabundant population : Kinetic ≠ Chemical equilibrium

$$\boxed{\frac{n_\chi}{n_\chi^{\rm th}} \sim \frac{(\Gamma_\phi^\chi H M_P^2)^{1/4}}{m_\phi} \sim \frac{T'}{m_\phi} \lesssim 1}$$

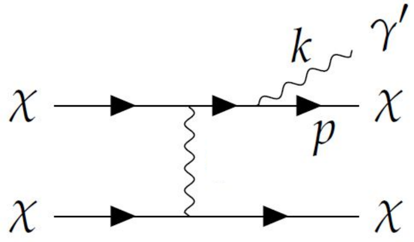
2-2 processes redistribute momenta but **chemical equilibration** must involve **particle number changing processes**

→ finite thermalization time through **splitting processes**



Thermalization in an Abelian plasma

In an **abelian plasma** thermalization proceeds through **gauge boson emission**



Multiple soft scatterings broaden the parent fermion transverse momentum, while the dark photon does not undergo efficient soft rescattering ➜ **Landau-Pomeranchuk-Migdal (LPM) suppression**

$$\Gamma^A_{2-3} \sim \alpha' \, \Gamma^s_{2-2} \sqrt{\frac{k}{k^A_{\rm LPM}}}$$

$$k^A_{\rm LPM} \sim \frac{p^4}{n_\chi}$$

LPM-suppressed splittings

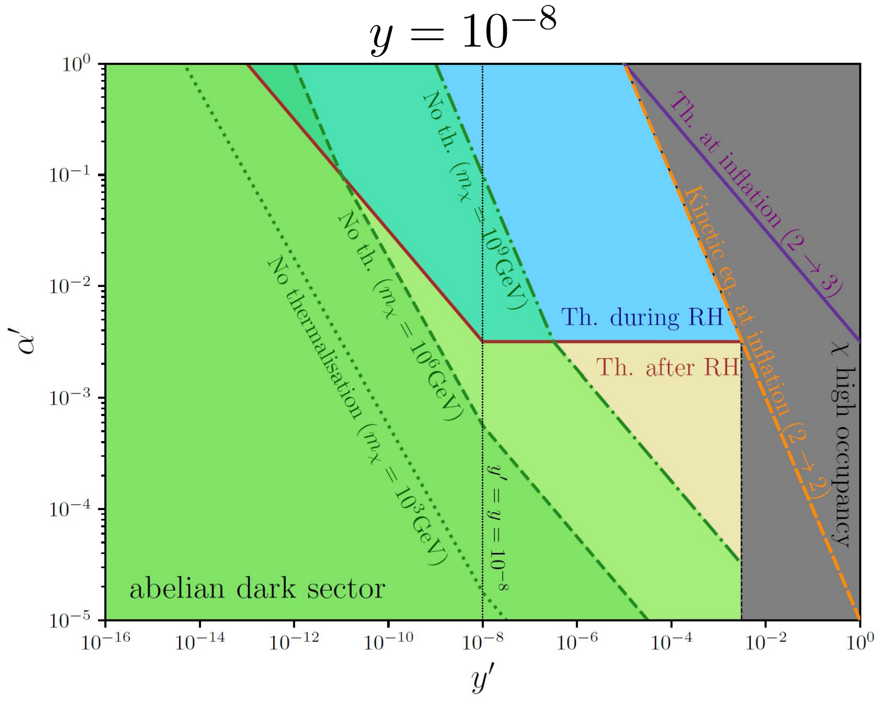
Abelian thermalization: **relatively hard gauge bosons are produced first**, followed by a **cascade toward lower momenta** through repeated splittings

➜ **Bottleneck : LPM suppressed gauge boson emission**

$$\boxed{t^{\rm A}_{\rm th} \sim 1/\Gamma_{2\to3} \sim \frac{1}{\alpha'^2 m_\phi}\left(\frac{m_\phi^3}{n_\chi}\right)^{1/2}}$$

SC, Kimus, Tytgat, **2605.09686**

Constraints from Thermalization of the Hidden Sector



Domain of thermalization
during/after reheating
Abelian plasma

blue region : thermalization via fast splitting processes before reheating ends

yellow region : thermalization via fast splitting processes only after reheating ends

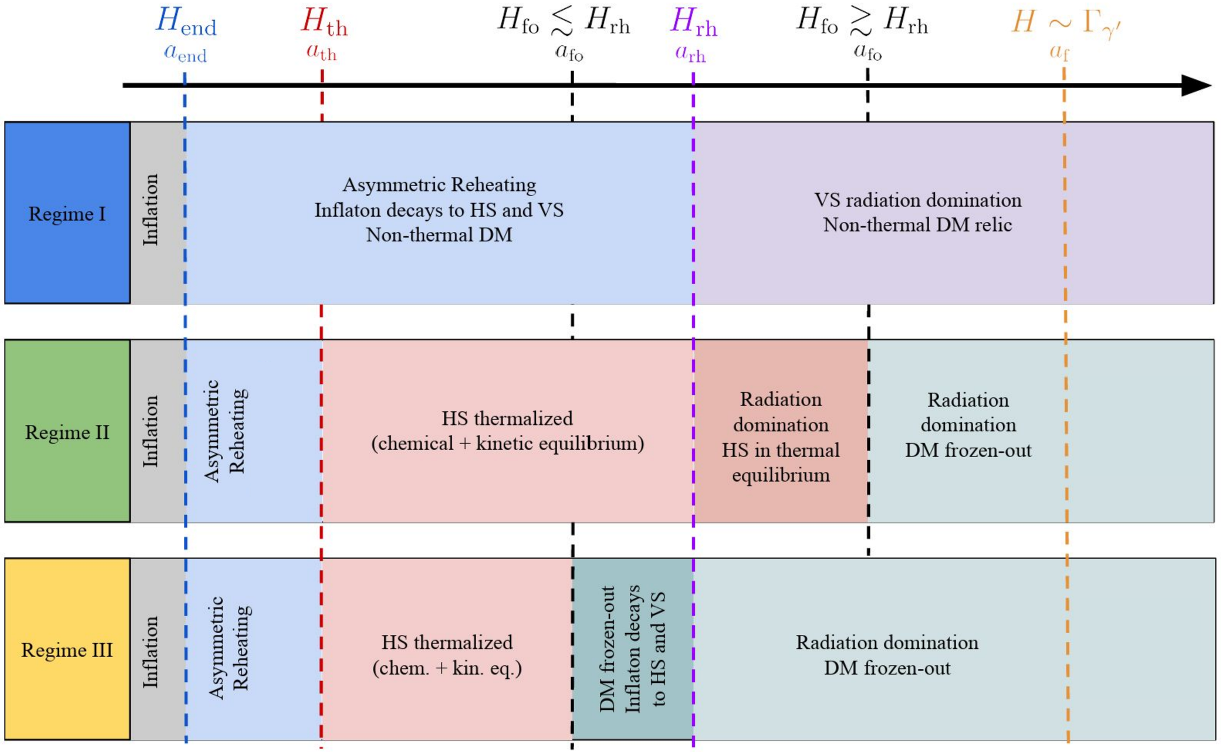
green regions : dark electrons become non-relativistic too early

$$m_\chi > T'_{\rm th}$$

grey region : outside the dilute perturbative regime (initial high occupancy and/or strong coupling)

SC, Kimus, Tytgat, **2605.09686**

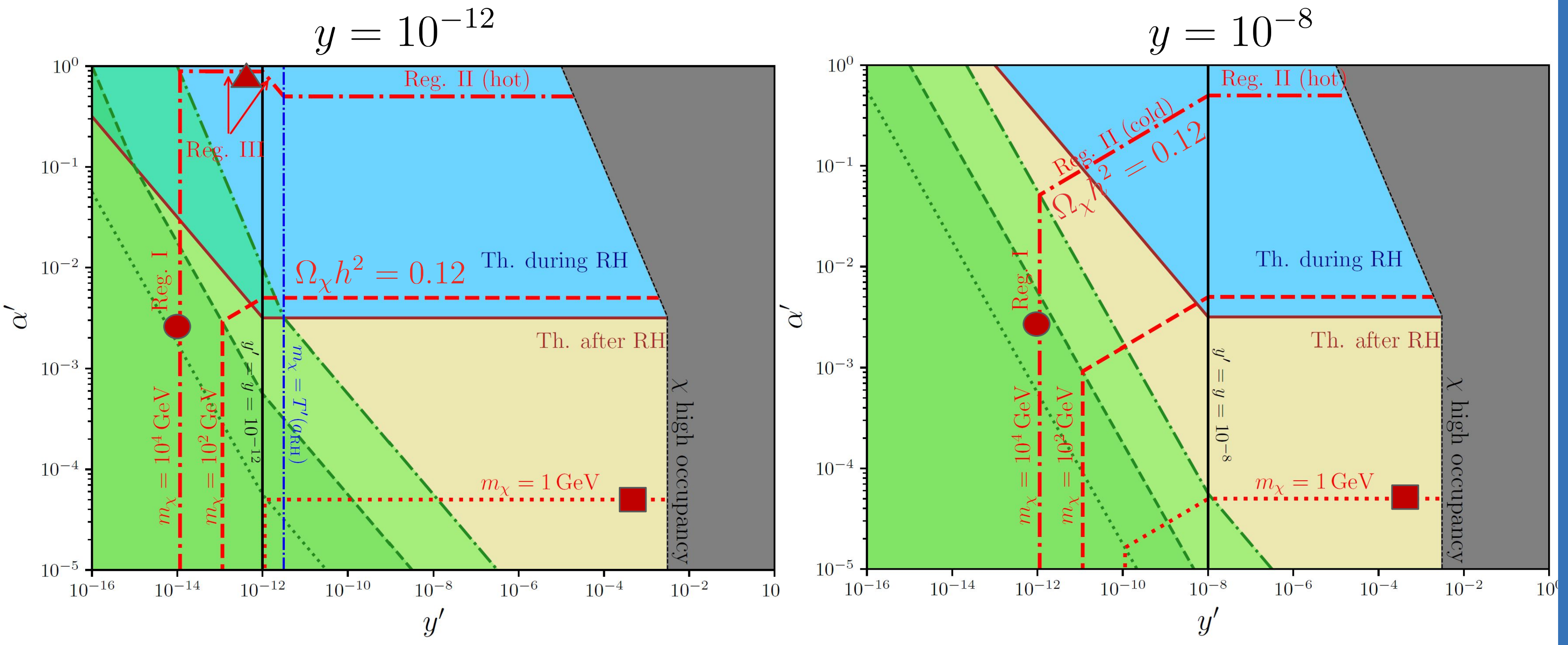
Reheating and DM production scenarios



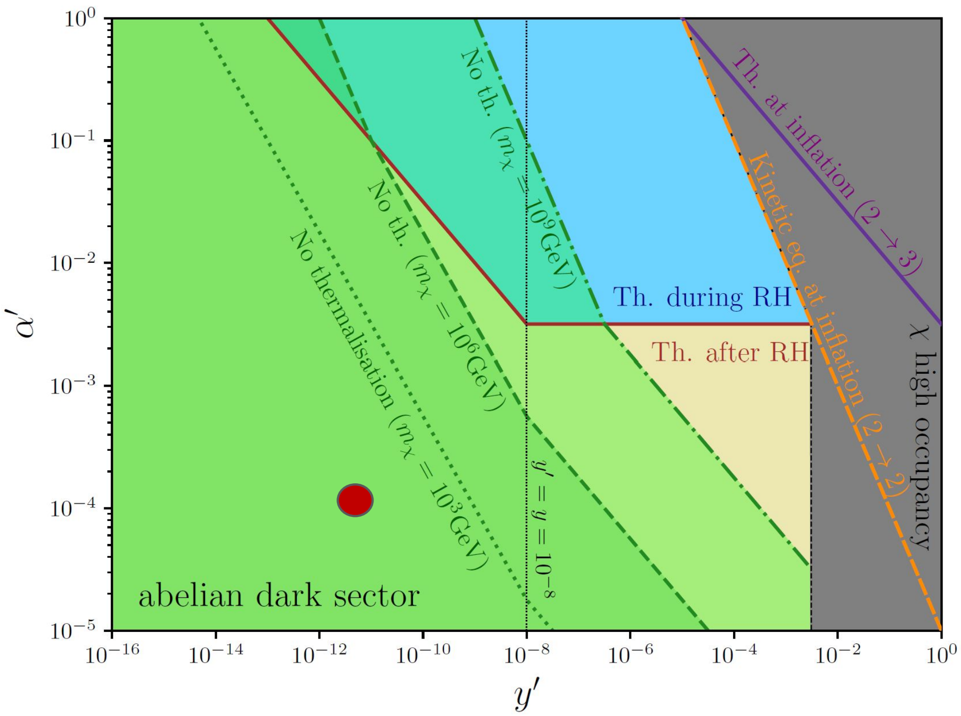
3 regimes :

- **Non-thermal** DM produced from inflaton decays **(Regime I)**
- Thermalization + **Freeze-out after reheating (Regime II)**
- Thermalization + **Freeze-out during reheating (Regime III)**

Mapping the Regimes



Non-thermal production from inflaton decays (Regime I)



Thermalization is **not reached** before χ is non-relativistic and HS is **subdominant (y' < y)**

➜ **Non-thermal production** sourced by the **inflaton decays**

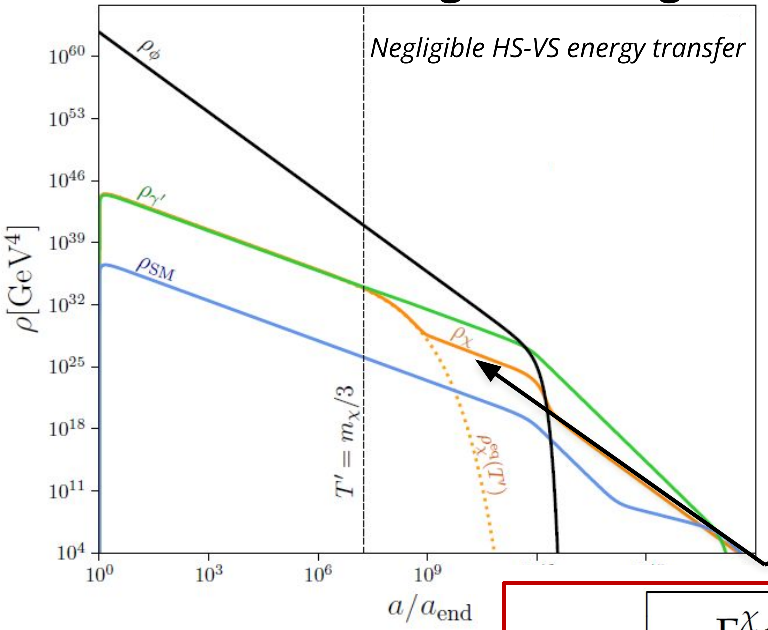
$$Y_\chi = \frac{n_\chi}{s} \sim \frac{\Gamma_\phi^\chi M_P^{1/2}}{m_\phi H_{\rm rh}^{1/2}} \sim y'^2 y^{-1} \left(\frac{M_P}{m_\phi}\right)^{1/2}$$

$$\downarrow$$

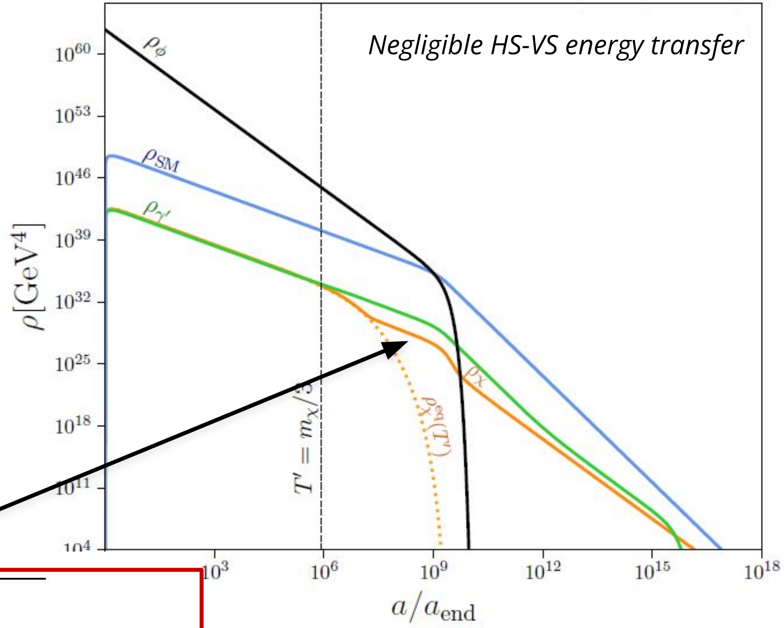
$$\boxed{m_\chi \sim \xi_i^{-4} \left(\frac{10^{-11}}{y}\right) \text{GeV}}$$

Freeze-out during Reheating (Regime III)

Dominant HS (T’ > T)
Freeze-out **during** Reheating



Sub-dominant HS (T’ < T)
Freeze-out **during** Reheating



$$T'(a_{\mathrm{RH}}) \ll m_\chi$$

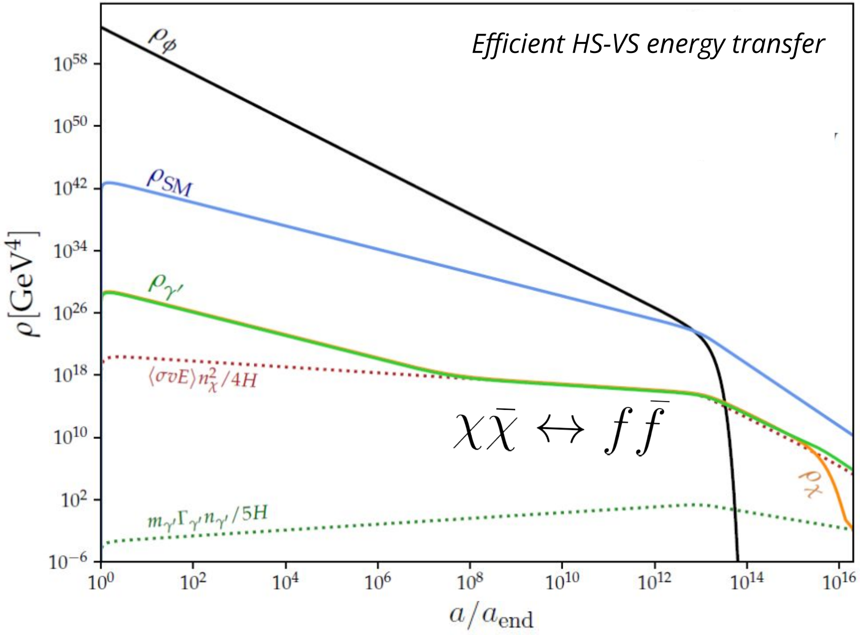
$$\boxed{\rho_\chi \sim \sqrt{\frac{\Gamma_\phi^\chi m_\chi^2}{\langle \sigma_{\chi-\gamma'} v E\rangle_0}\rho_\phi} \propto a^{-3/2}}$$

“Re-sourcing ”

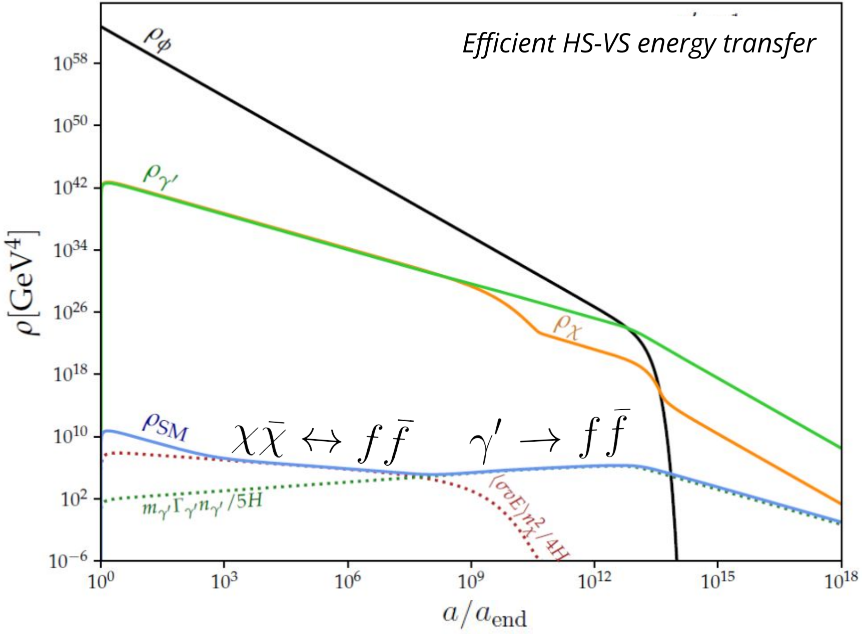
Evolution of the temperature ratio ξ

HS-VS interactions can affect the temperature ratio by sourcing one sector from the other

Sub-dominant HS (cold T' < T)

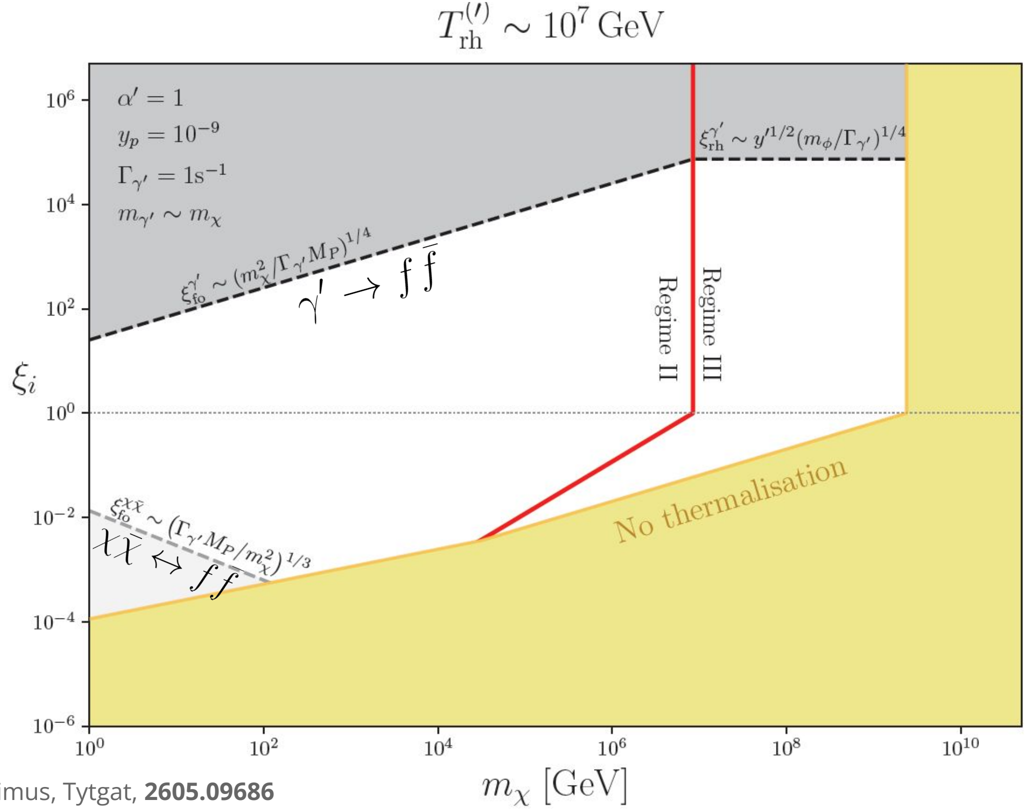


Dominant HS (hot T' > T)



Evolution of the temperature ratio ξ

Domain of stability of the temperature ratio ξ

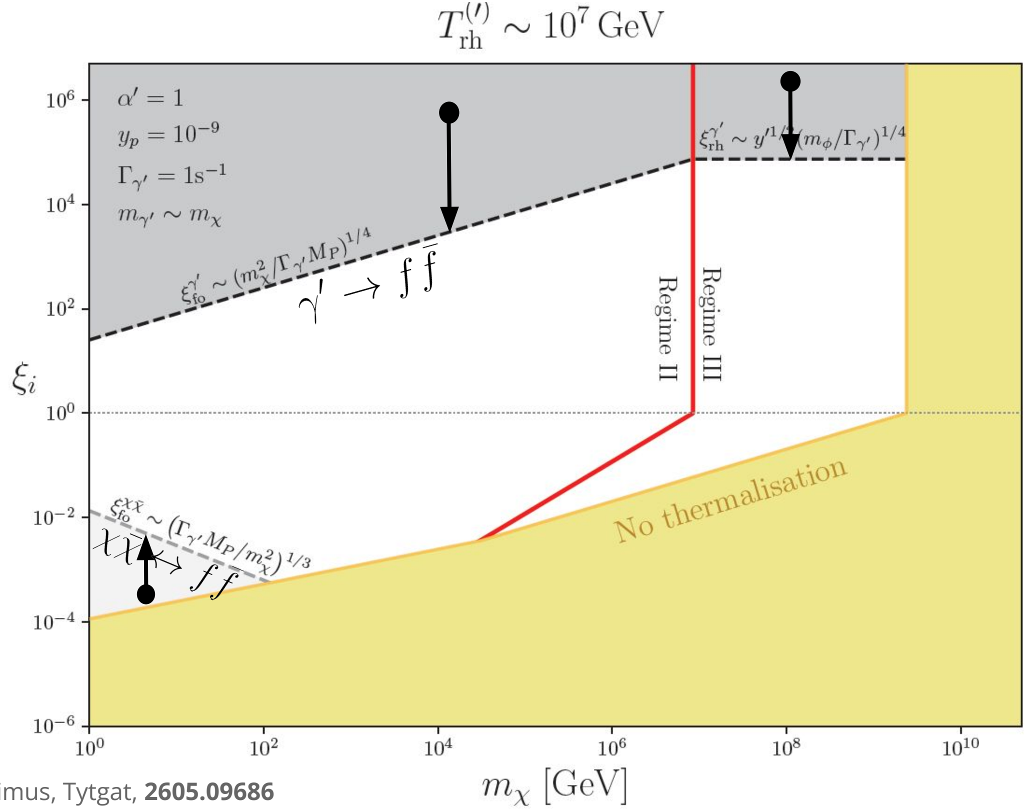


SC, Kimus, Tytgat, **2605.09686**

- A **too large** ($\xi \gg$ 1) or **too low** ($\xi \ll$ 1) is **driven closer to 1**
- ξ **at DM decoupling** on the dashed line boundaries depending on **which process drives energy transfer** and **whether freeze-out occurs during or after reheating (red frontier)**
- **Upper bound on ξ for hot HS from dark photons decay before BBN**

Evolution of the temperature ratio ξ

Domain of stability of the temperature ratio ξ



SC, Kimus, Tytgat, **2605.09686**

- A **too large** ($\xi \gg 1$) or **too low** ($\xi \ll 1$) is **driven closer to 1**
- **ξ at DM decoupling** on the dashed line boundaries depending on **which process drives energy transfer** and **whether freeze-out occurs during or after reheating (red frontier)**
- **Upper bound on ξ for hot HS from dark photons decay before BBN**

Thermal Dark Matter domains in Dark QED

Unitarity limit $\boxed{\langle\sigma_{\chi\bar{\chi}-\gamma'\gamma'}v\rangle_{\rm fo} \lesssim \frac{4\pi}{m_\chi^2}\frac{K_2(2m_\chi/T')}{K_2^2(m_\chi/T')}}$

Here : Freeze-out after reheating
+ maximal entropy dilution

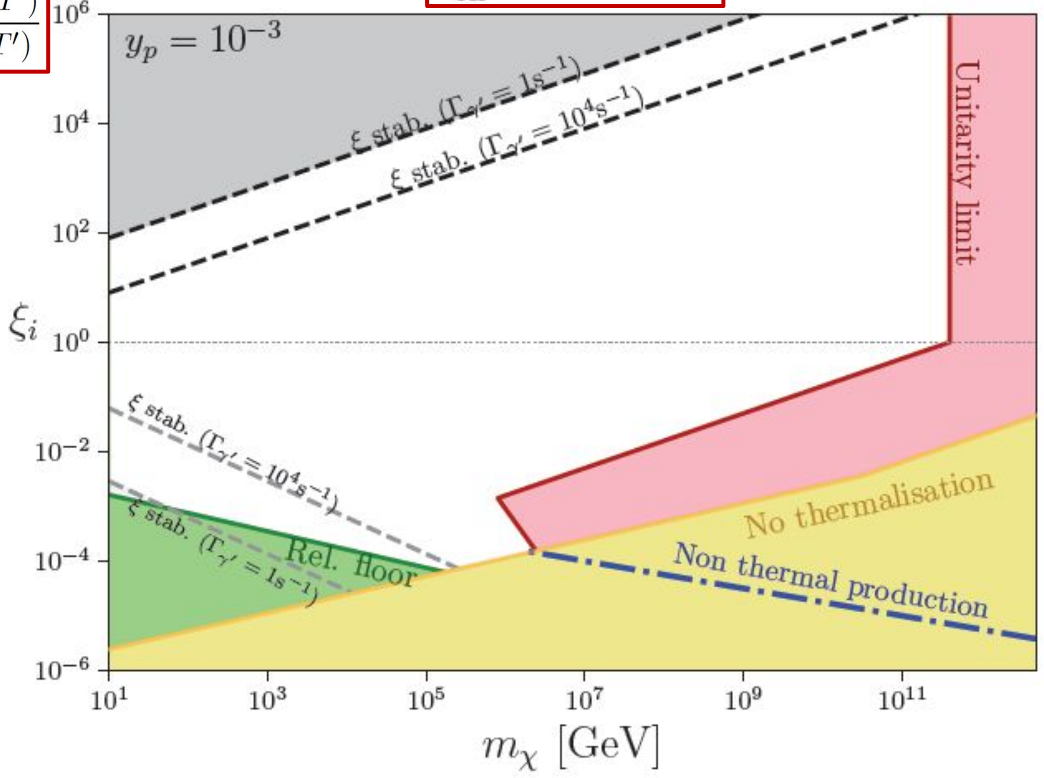
Maximum ξ imposed by **minimal dark photon decay width (BBN)**
ξ driven to the edge of the region

Constraint from **thermalization** timescale **after reheating** $m_\chi > T'_{\rm th}$

Observed relic abundance from non-thermal **inflaton decays**

Maximal relic from **relativistic freeze-out**; below **relativistic floor** DM is under abundant

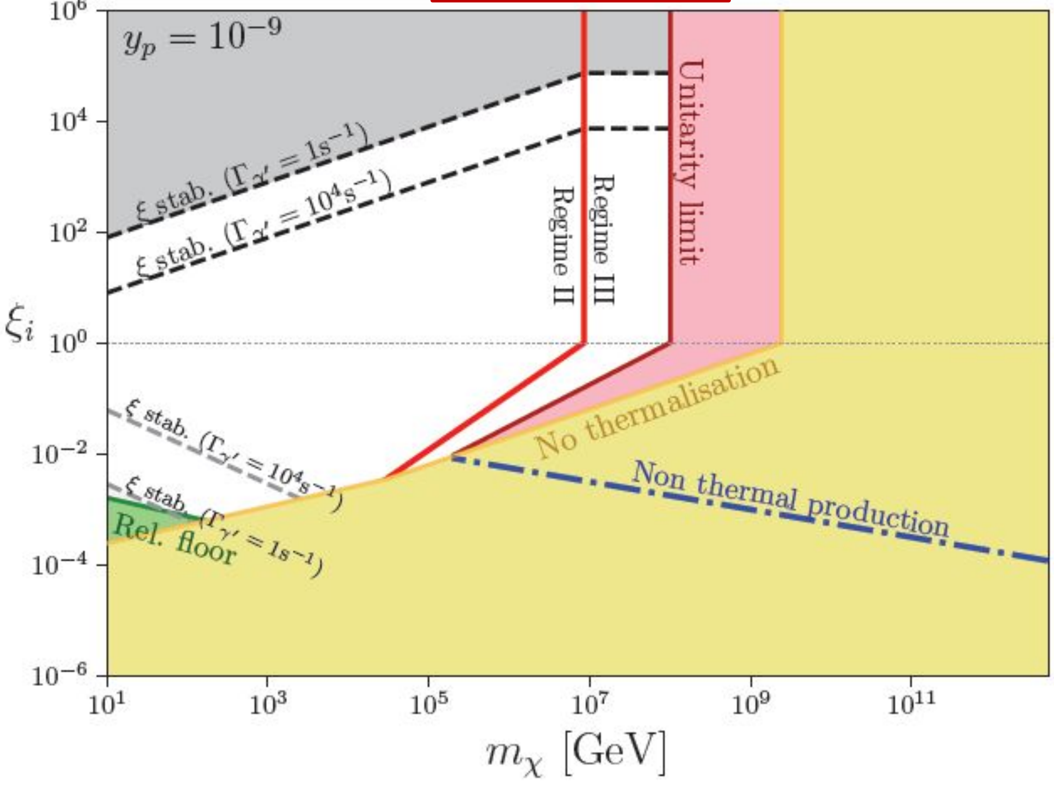
$\boxed{T_{\rm rh}^{(\prime)} \sim 10^{12}\text{GeV}}$



SC, Kimus, Tytgat, **2605.09686**

Thermal Dark Matter domains in Dark QED

$T_{\mathrm{rh}}^{(\prime)} \sim 10^7\,\mathrm{GeV}$



SC, Kimus, Tytgat, **2605.09686**

Freeze-out after/during reheating (Regimes II/III)

Maximum ξ depends on the regime of **freeze-out after/during reheating**

Freeze-out during reheating: upper bounds from unitarity affected by reheating

Constraint from **thermalization** time scale **during reheating** $m_\chi > T'_{\mathrm{th}}$

Summary

- **Abelian HS thermalization** can be significantly **delayed by LPM-suppressed splittings**
- **Distinct DM relic histories arise : non-thermal inflaton decays, freeze-out after reheating or freeze-out during reheating**
- Temperature ratio **$\xi = T'/T$** is **not necessarily stable** and can evolve throughout reheating until DM freeze-out. **We identify a domain of stability, affected by reheating**
- **Reheating and thermalization shape the thermal DM domain** on the HS-VS **temperature ratio at Freeze-out** and on the **viable DM mass range**

Outlook :

- Non-perturbative / highly occupied regimes during (p)reheating
- Late energy injection from a subdominant dark-photon population ?
- Connection to SIDM phenomenology

Summary

- **Abelian HS thermalization** can be significantly **delayed by LPM-suppressed splittings**
- **Distinct DM relic histories arise : non-thermal inflaton decays, freeze-out after reheating or freeze-out during reheating**
- Temperature ratio **$\xi = T'/T$** is **not necessarily stable** and can evolve throughout reheating until DM freeze-out. **We identify a domain of stability, affected by reheating**
- **Reheating and thermalization shape the thermal DM domain** on the HS-VS **temperature ratio at Freeze-out** and on the **viable DM mass range**

Outlook :

- Non-perturbative / highly occupied regimes during (p)reheating
- Late energy injection from a subdominant dark-photon population ?
- Connection to SIDM phenomenology

Thank you for your attention !

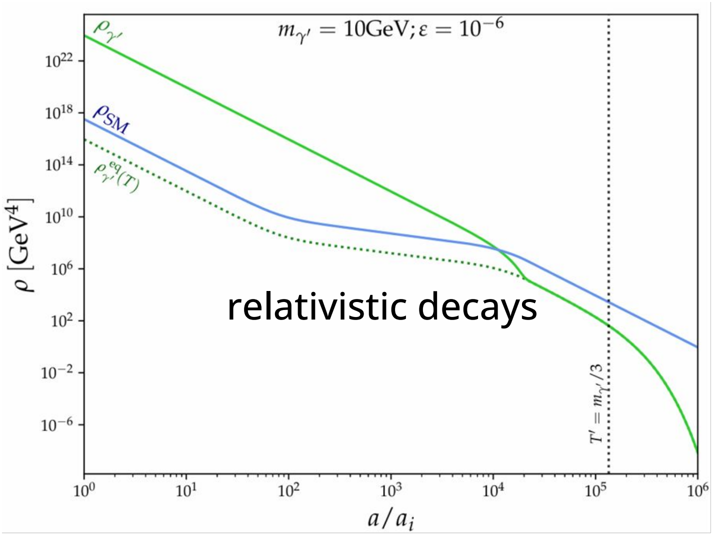
Backup

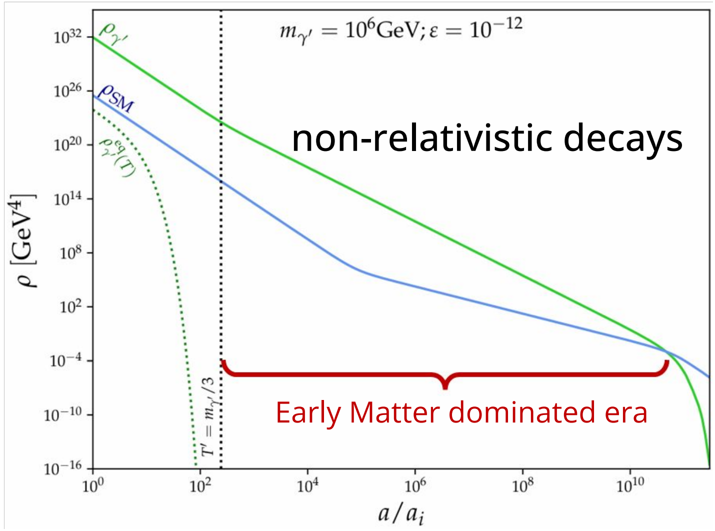
Dark Photons decay and entropy dilution

Assumptions:

- ✦ DM particles **freeze-out before dark photons decay** $m_{\gamma'} \lesssim m_\chi$
- ✦ **Dark photons free-stream after DM freeze-out**, with an **initially relativistic thermal spectrum**
- ✦ Dark photons **decay before BBN** $\Gamma_{\gamma'} \gtrsim 1\,\mathrm{s}^{-1}$

➜ Massive particles decay may **increase the total comoving entropy if they are dominant**

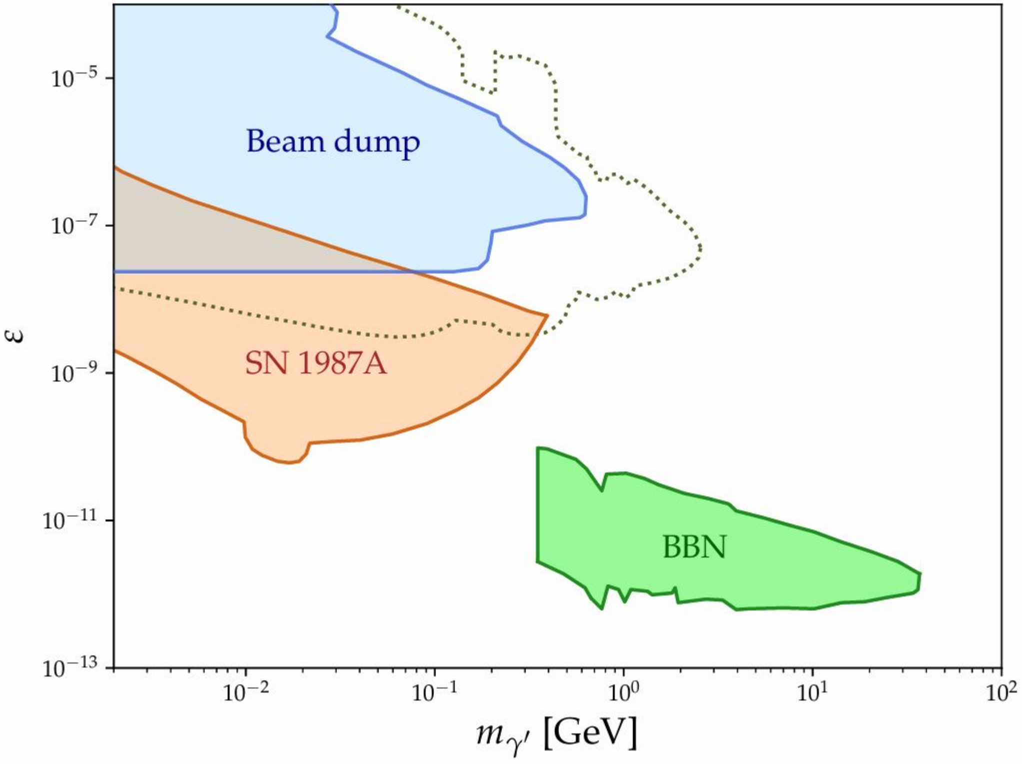




➜ Large entropy injection

Observational/Experimental constraints on massive Dark Photons

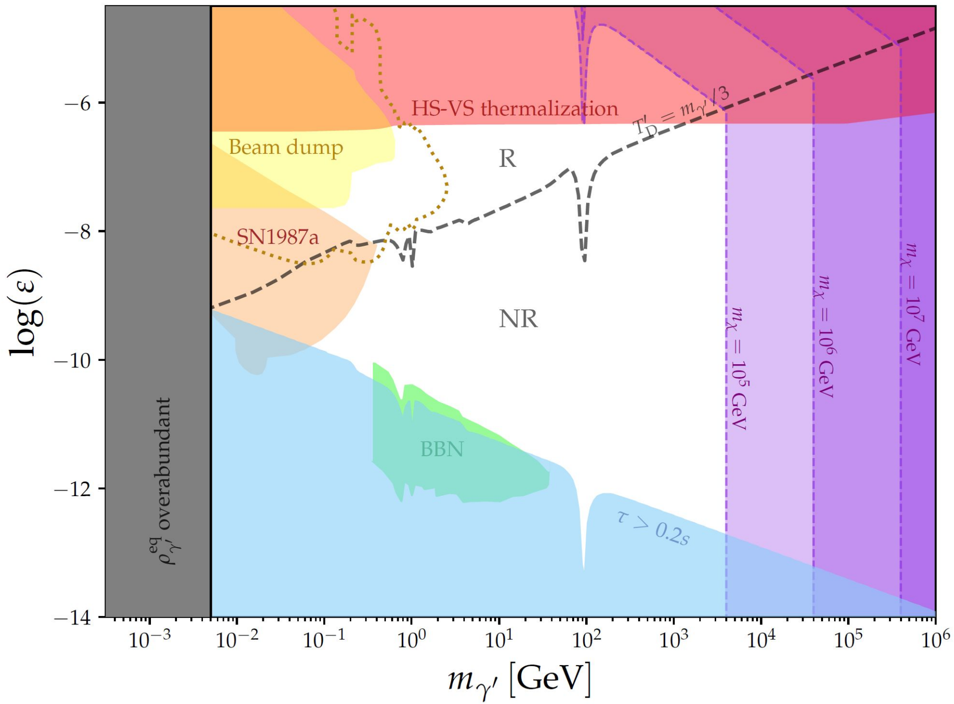
- Beam dump : absence of additional feeble interaction channels for fixed target experiments (E137, LSND, CHARM, NuCal, and projected as SHiP)
- SN 1987 A : absence of additional energy loss processes in observed ν flux from Supernovae
- BBN : Nucleosynthesis abundances not disrupted by frozen-in Dark Photons



For more see *The Heavy Dark Photon Handbook: Cosmological and Astrophysical Bounds,* Caputo, Park, Yun **2511.15785**

Domain of (dominant) Dark Photons

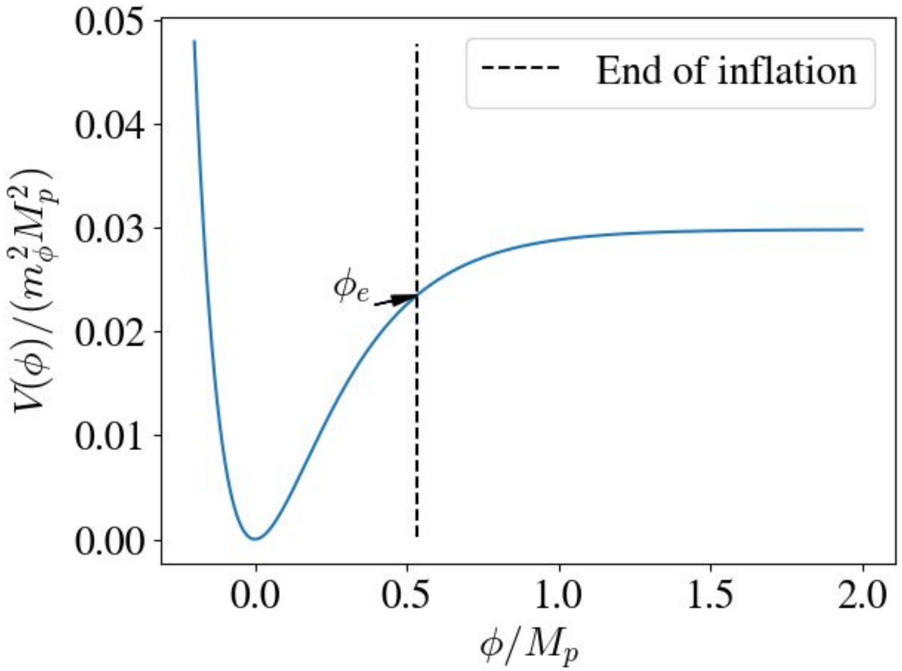
- ✦ Experimental and observational constraints
- ✦ Decay before BBN (and subdominant freeze-in abundance)
- ✦ Too abundant relativistic dark photons at BBN
- ✦ DM freeze-out in the HS and stays secluded ($\chi\bar{\chi} \to f\bar{f}$, do not lead to T=T')
- ✦ DM freeze-out in the HS $m_{\gamma'} < m_\chi / x'_{\text{fo}}$ and stays secluded ($\gamma' \to f\bar{f}$, do not lead to T = T')
- ✦ Separation between Relativistic (R) and Non Relativistic (NR) dark photon decay scenarios



Light from darkness: History of a hot Dark Sector, Coy, Kimus, Tytgat, **2405.10792**

For more see *The Heavy Dark Photon Handbook: Cosmological and Astrophysical Bounds*, Caputo, Park, Yun **2511.15785**

Starobinsky inflation



$$V(\phi) = \frac{3}{4} m_\phi^2 M_P^2 \left(1 - e^{-\sqrt{\frac{2}{3}}\frac{\phi}{M_P}}\right)^2$$

$$\boxed{m_\phi \simeq 3 \times 10^{13}\ \text{GeV}}$$

$$\Big\downarrow \; \phi \ll M_P$$

$$V(\phi) \approx \tfrac{1}{2} m_\phi^2 \phi^2$$

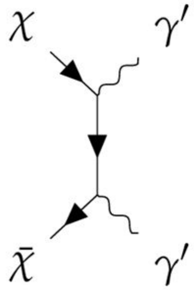
$$\boxed{w_\phi = P_\phi/\rho_\phi \simeq 0}$$

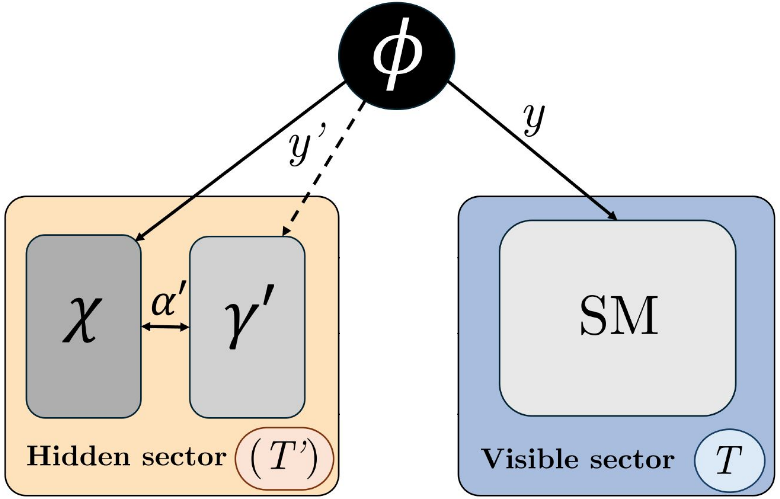
Quadratic potential near the minimum

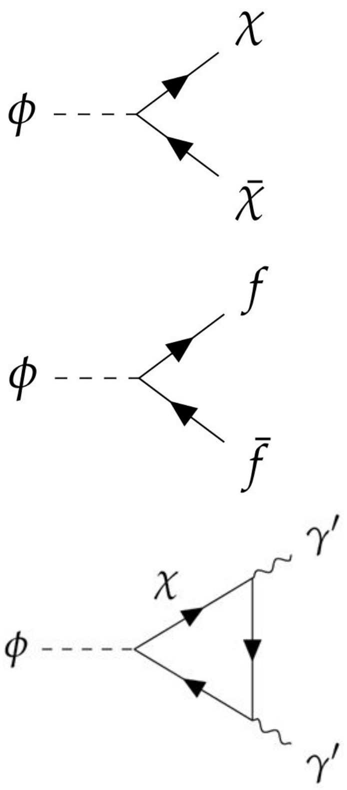
Asymmetric Reheating

A way to produce the HS, via **asymmetric energy transfer** from inflaton to both HS and VS

$$\mathcal{L} \supset \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi) - y\phi\bar{f}f - y'\phi\bar{\chi}\chi$$
$$+\,\bar{\chi}\left(i\not{D} - m_\chi\right)\chi - \frac{1}{4}F'^{\mu\nu}F'_{\mu\nu} + \frac{1}{2}m_{\gamma'}A'_\mu A'^\mu - \frac{\epsilon}{2}B_{\mu\nu}F^{\mu\nu}$$





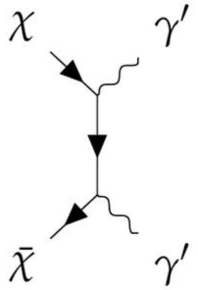


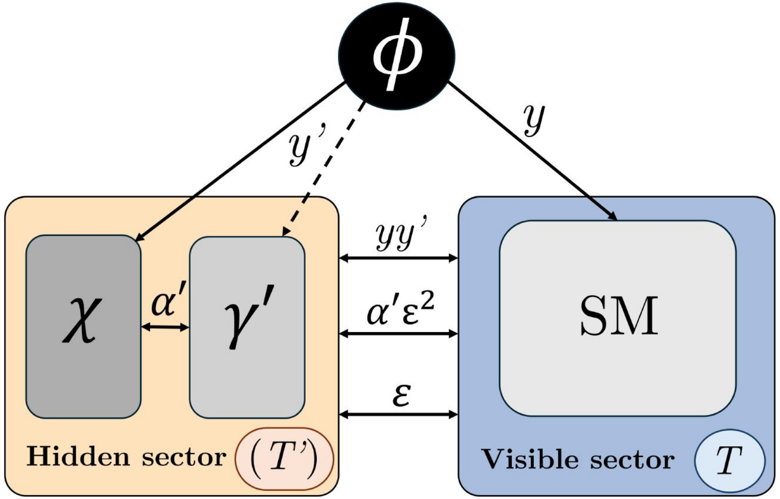
Asymmetric Reheating

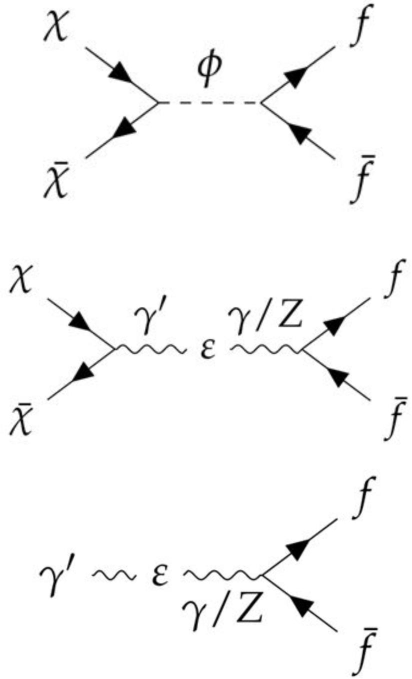
Asymmetric Reheating

A way to produce the HS, via **asymmetric energy transfer** from inflaton to both HS and VS

$$\mathcal{L} \supset \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi) - y\phi\bar{f}f - y'\phi\bar{\chi}\chi$$
$$+ \bar{\chi}\left(i\not{D} - m_\chi\right)\chi - \frac{1}{4}F'^{\mu\nu}F'_{\mu\nu} + \frac{1}{2}m_{\gamma'}A'_\mu A'^\mu - \frac{\epsilon}{2}B_{\mu\nu}F^{\mu\nu}$$







Contact between SM and HS

Boltzmann equations

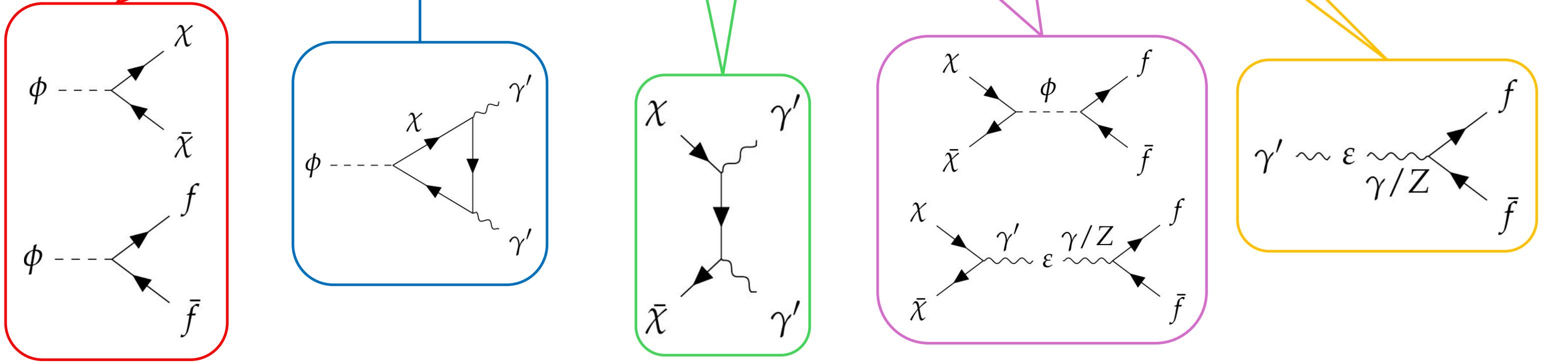
Boltzmann equations for **thermal** HS and SM solved numerically

$$\dot{\rho}_\phi + 3H\rho_\phi = -\Gamma_\phi\rho_\phi$$

$$\dot{\rho}_\chi + 3(1+w_\chi)H\rho_\chi = \Gamma^{\chi}_{\phi}\rho_\phi - \langle\sigma_{\chi-\gamma'}vE\rangle_{T'}\left(n_\chi^2 - \left(n_\chi^{\mathrm{eq}}(T')\right)^2\right) - \langle\sigma_{\chi-f}vE\rangle_{T'}n_\chi^2 + \langle\sigma_{\chi-f}vE\rangle_{T}\left(n_\chi^{\mathrm{eq}}(T)\right)^2$$

$$\dot{\rho}_{\gamma'} + 3(1+w_{\gamma'})H\rho_{\gamma'} = \Gamma^{\gamma'-\mathrm{loop}}_{\phi}\rho_\phi - \langle\sigma_{\chi-\gamma'}vE\rangle_{T'}\left(n_\chi^2 - \left(n_\chi^{\mathrm{eq}}(T')\right)^2\right) - m_{\gamma'}\Gamma_{\gamma'}\left(n_{\gamma'} - n_{\gamma'}^{\mathrm{eq}}(T)\right)$$

$$\dot{\rho}_{\mathrm{SM}} + 4H\rho_{\mathrm{SM}} = \Gamma^{\mathrm{SM}}_{\phi}\rho_\phi + \langle\sigma_{\chi-f}vE\rangle_{T'}n_\chi^2 - \langle\sigma_{\chi-f}vE\rangle_{T}\left(n_\chi^{\mathrm{eq}}(T)\right)^2 + m_{\gamma'}\Gamma_{\gamma'}\left(n_{\gamma'} - n_{\gamma'}^{\mathrm{eq}}(T)\right)$$

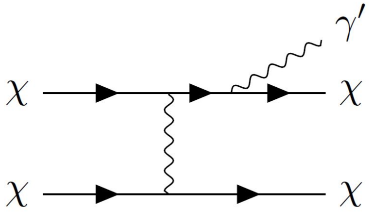


SC, Kimus, Tytgat, **2605.09686**

Thermalization of the Hidden Sector : Splittings

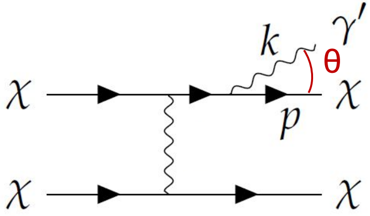
Gauge boson emission dominated by **soft t-channel collision of hard fermions** of density n_h

➜ slightly off-shell parent fermion radiating a gauge boson
➜ splitting rate from soft collision cut off in the medium by the Debye mass $m_D^2 \sim \alpha' \int d^3k \frac{f(k)}{k}$



$$\Gamma_{2\to 3} \sim \alpha' \, \Gamma^s_{2\to 2} \longleftarrow \Gamma^{\boxed{s}}_{2\to 2} \sim \begin{cases} \boxed{\alpha' m_\phi} & m_D \gtrsim m_{\gamma'} \\ \alpha'^2 n_h / \bar{m}^2_{\gamma'}, & m_{\gamma'} \gtrsim m_D \end{cases}$$

Emitted soft gauge bosons are **collinear** with their parent particle
➜ a finite time before the particles are **"separated"**



Several amplitudes interfering destructively can **suppress the splitting rate ➜ Landau–Pomeranchuk–Migdal (LPM) effect**

Thermalization timescales : Abelian vs Non-Abelian

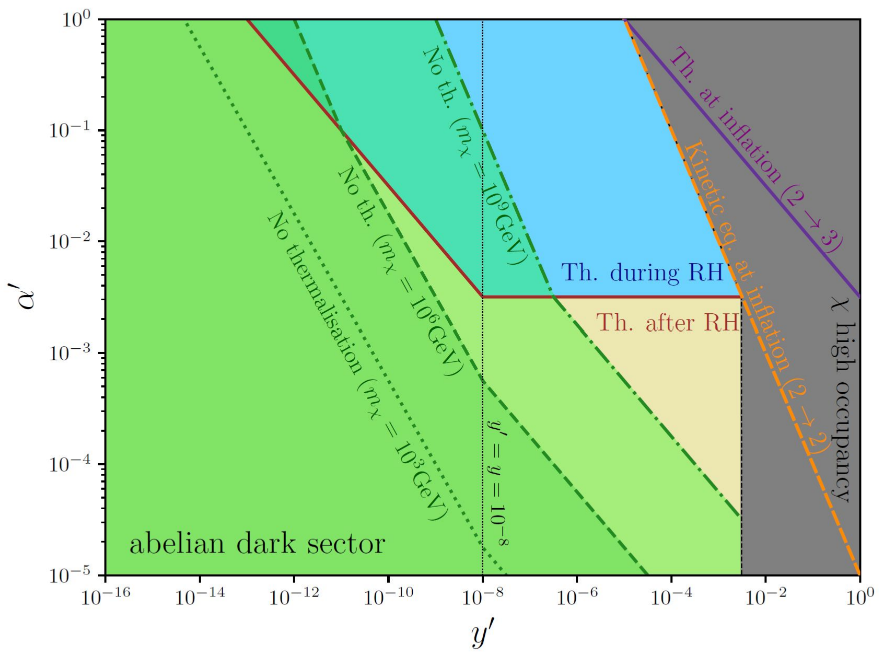
	abelian	non-abelian
LPM	$k \gtrsim k_{\mathrm{LPM}}$	$k \lesssim k_{\mathrm{LPM}}$
k_{LPM}	$\frac{m_\phi^4}{n_h} \gg m_\phi$	$\frac{n_h}{m_\phi^2} \ll m_\phi$
$\Gamma_{2\to 3}^{\mathrm{LPM}}$	$\alpha' \Gamma_{2-2}^s \sqrt{\frac{k}{k_{\mathrm{LPM}}}}$	$\alpha' \Gamma_{2-2}^s \sqrt{\frac{k_{\mathrm{LPM}}}{k}}$
t_{th}	$\frac{1}{\alpha'^2 m_\phi} \left(\frac{m_\phi^3}{n_h}\right)^{1/2}$	$\frac{1}{\alpha'^2 m_\phi} \left(\frac{m_\phi^3}{n_h}\right)^{3/8}$
H_{th}	$m_\phi\, \alpha'^4 \left(\frac{\Gamma_\phi^\chi M_P^2}{m_\phi^3}\right)$	$m_\phi\, \alpha'^{16/5} \left(\frac{\Gamma_\phi^\chi M_P^2}{m_\phi^3}\right)^{3/5}$

SC, Kimus, Tytgat, **2605.09686**

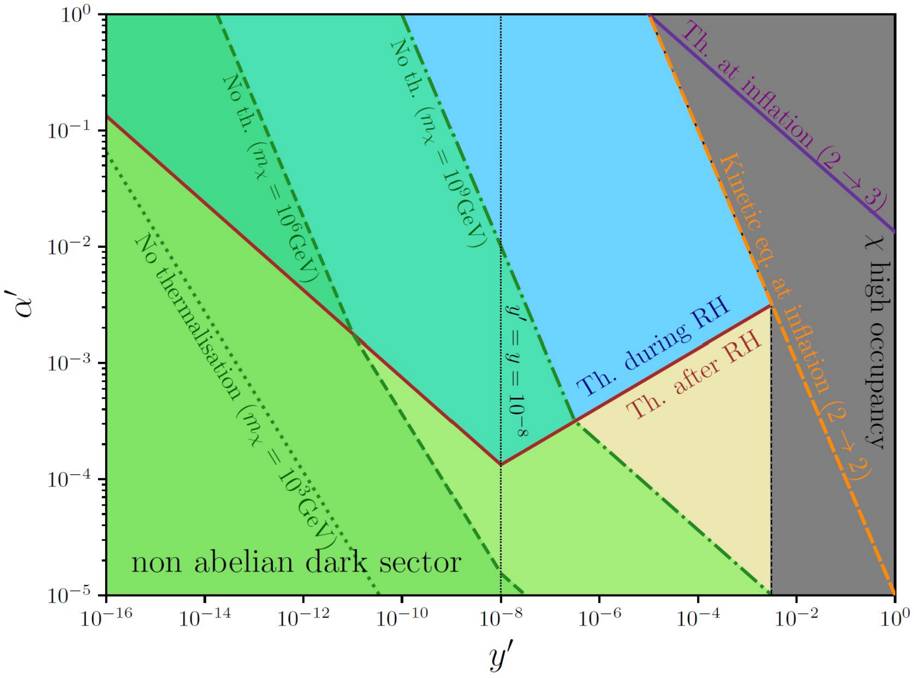
Thermalization timescales, to compare with reheating time scale

Harigaya, Mukaida, **1312.3097**

Constraints from Thermalization of the Hidden Sector



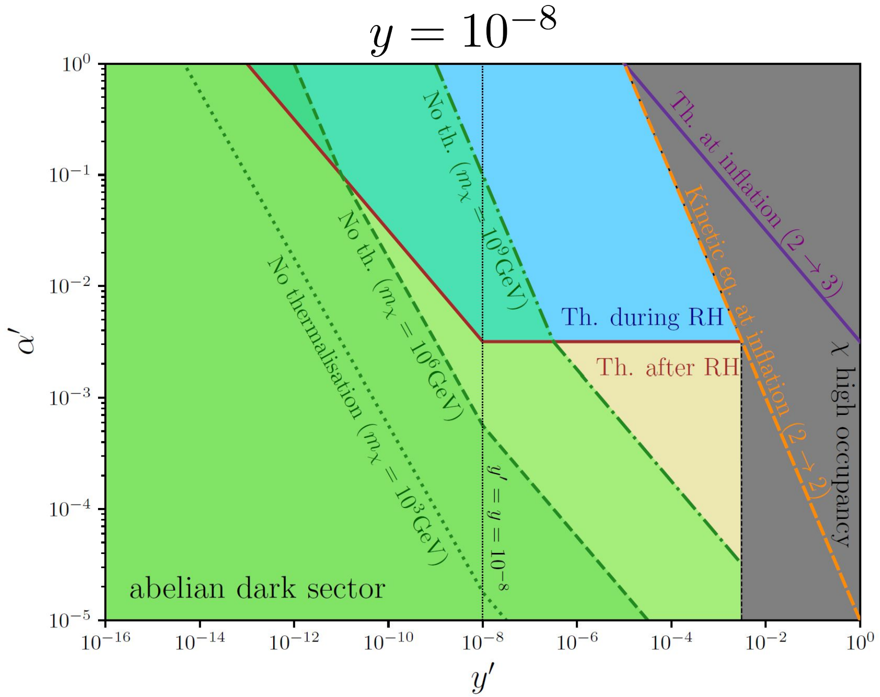
Domain of thermalization
during/after reheating
Abelian plasma



Domain of thermalization
during/after reheating
Non-Abelian plasma

SC, Kimus, Tytgat, **2605.09686**

Constraints from Thermalization of the Hidden Sector



Domain of thermalization
during/after reheating
Abelian plasma

grey region : initially abundant and/or strongly coupled HS

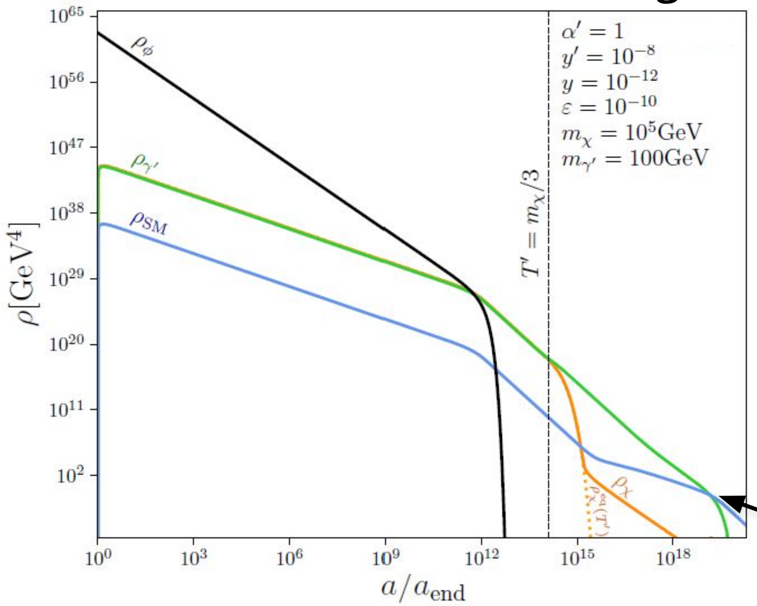
purple line: perturbative splitting processes are fast at the end of inflation

orange line: perturbative 2-2 scattering processes bring to kinetic equilibrium

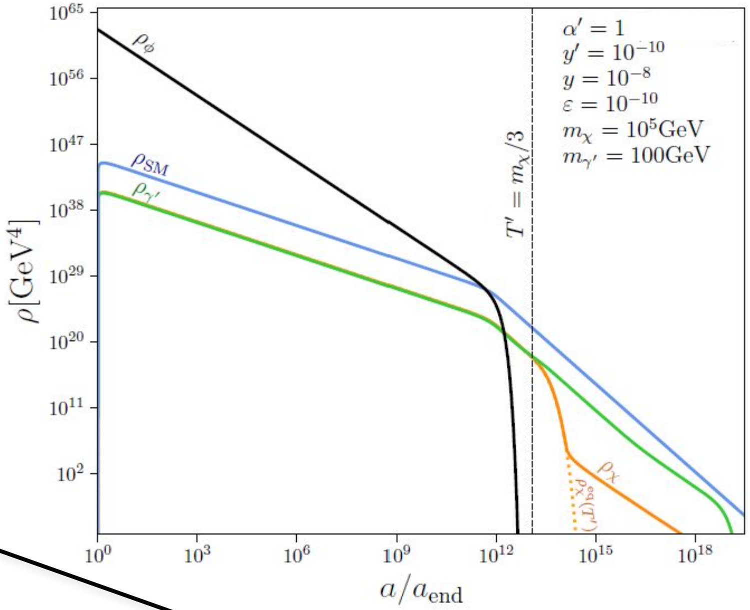
SC, Kimus, Tytgat, **2605.09686**

Freeze-out after Reheating (Regime II)

Dominant HS (T' > T)
Freeze-out after Reheating



Sub-dominant HS (T' < T)
Freeze-out after Reheating

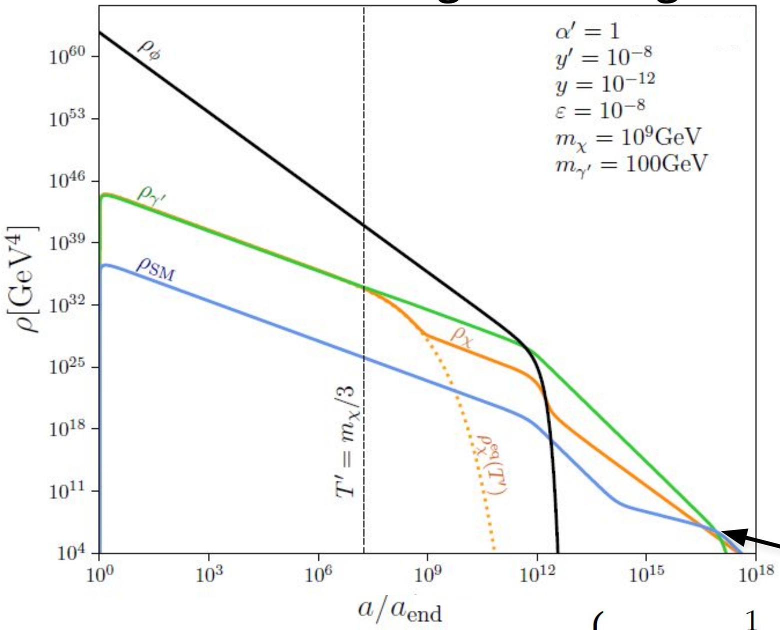


$$Y_\chi^{\rm fo} \equiv \frac{n_{\chi,\rm fo}}{s_{\rm t,\,fo}} \sim \frac{H_{\rm fo}}{\langle\sigma_{\chi-\gamma'}v\rangle_{T'_{\rm fo}}\left(H_{\rm fo}m_{\rm Pl}\right)^{3/2}} \to \begin{cases} \dfrac{1}{\langle\sigma_{\chi-\gamma'}v\rangle_{T'_{\rm fo}}\, m_{\rm Pl}m_\chi} & (y' \gg y) \\ \dfrac{\xi_{\rm fo}}{\langle\sigma_{\chi-\gamma'}v\rangle_{T'_{\rm fo}}\, m_{\rm Pl}m_\chi} & (y' \ll y) \end{cases}$$

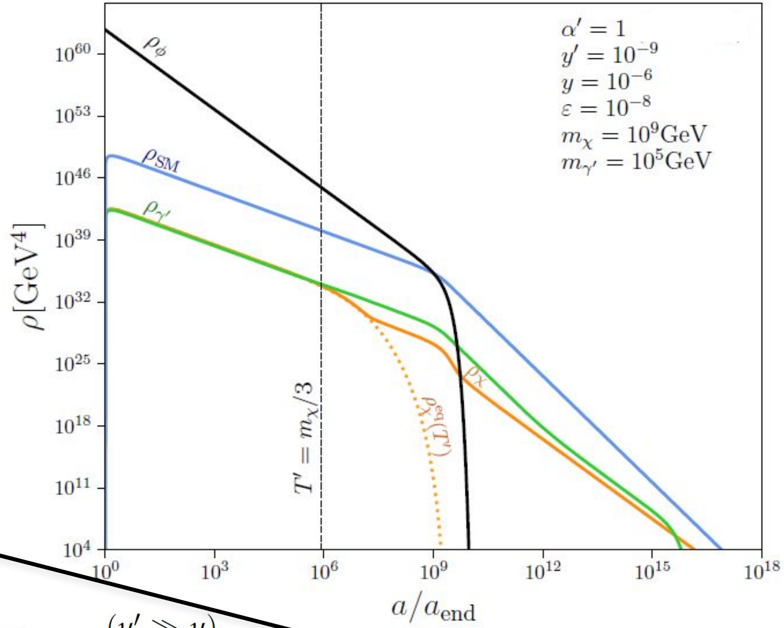
$$\times \quad \frac{s_{\rm t,\,fo}a_{\rm fo}^3}{s_{\rm t,\,f}a_{\rm f}^3} \sim \left(\frac{\Gamma_{\gamma'}}{H_{\rm nr}}\right)^{1/2}$$

Freeze-out during Reheating (Regime III)

Dominant HS (T’ > T) Freeze-out during Reheating



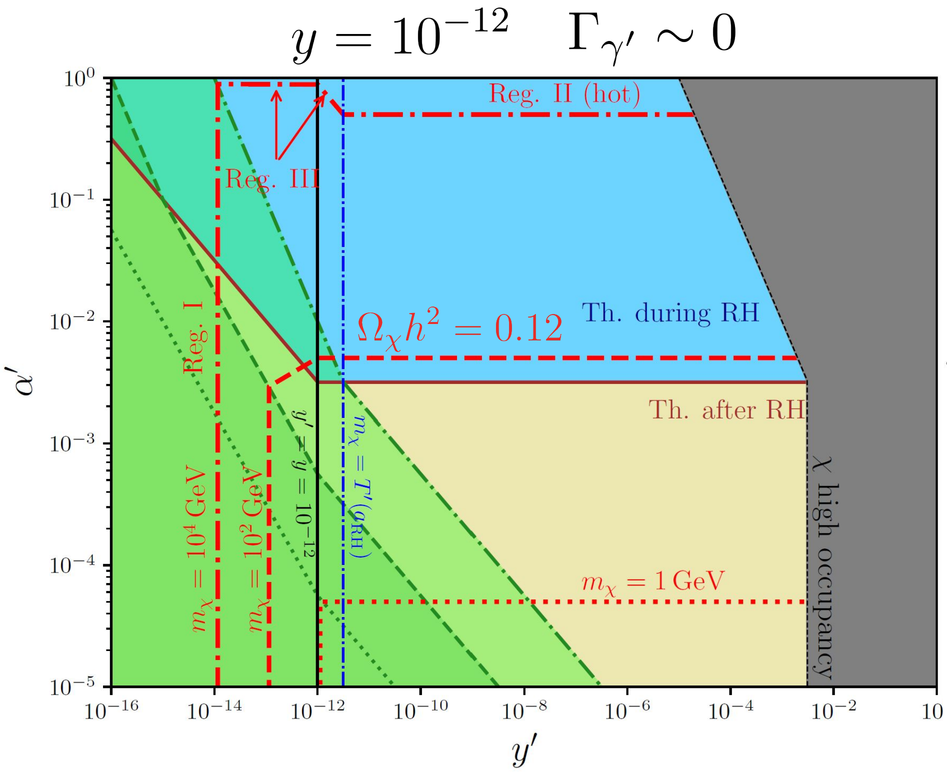
Sub-dominant HS (T’ < T) Freeze-out during Reheating

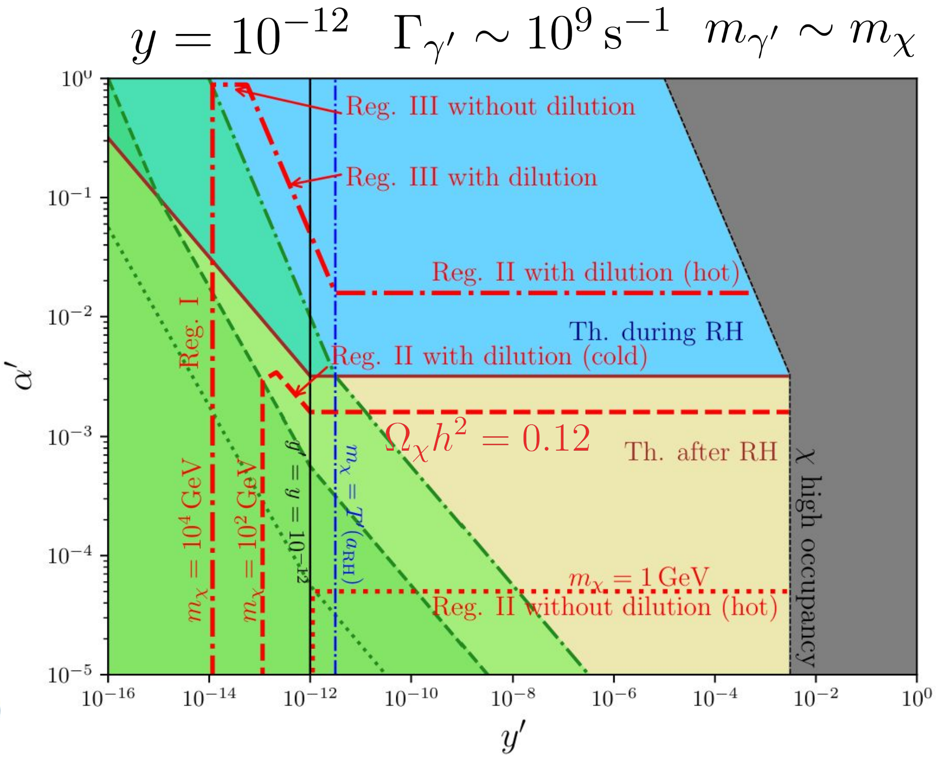


$$Y_\chi^{\mathrm{rh}} \equiv \frac{n_{\chi,\mathrm{rh}}}{s_{\mathrm{t,\,rh}}} \sim \frac{H_{\mathrm{rh}}}{\langle\sigma_{\chi-\gamma'}v\rangle_0\,(H_{\mathrm{rh}}m_{\mathrm{Pl}})^{3/2}} \to \begin{cases} \dfrac{1}{\langle\sigma_{\chi-\gamma'}v\rangle_0(\Gamma_\phi^\chi)^{1/2}m_{\mathrm{Pl}}^{3/2}} & (y' \gg y) \\ \dfrac{1}{\langle\sigma_{\chi-\gamma'}v\rangle_0(\Gamma_\phi^{\mathrm{SM}})^{1/2}m_{\mathrm{Pl}}^{3/2}} & (y' \ll y) \end{cases}$$

$$\times \quad \frac{s_{\gamma',\mathrm{rh}}a_{\mathrm{rh}}^3}{s_{\mathrm{SM,\,f}}a_{\mathrm{f}}^3} \sim \left(\frac{\Gamma_{\gamma'}}{H_{\mathrm{rh}}}\right)^{1/2}$$

Impact of dilution from Dark Photons decay

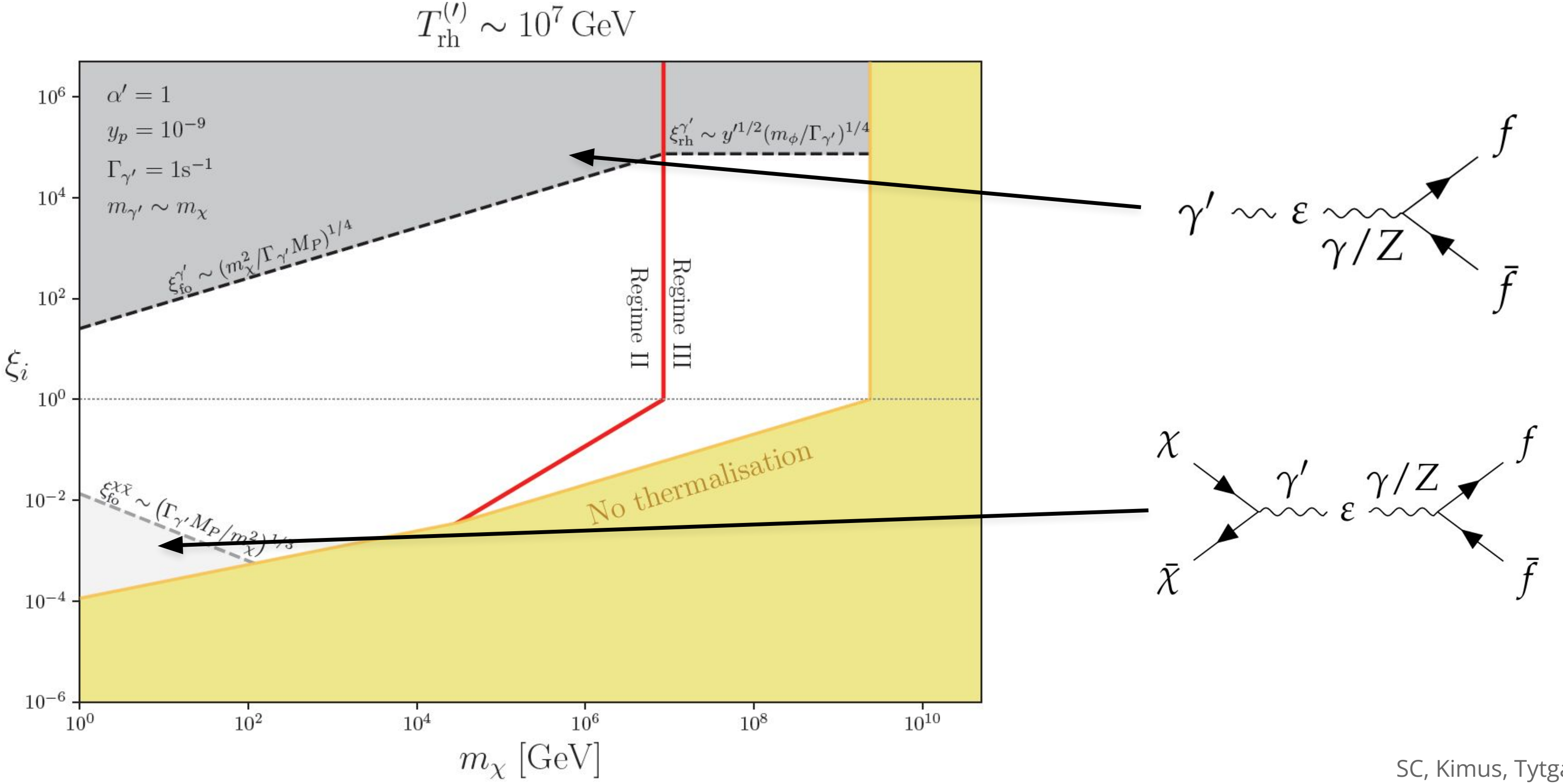




SC, Kimus, Tytgat, **2605.09686**

Evolution of the temperature ratio ξ

Domain of stability of the temperature ratio ξ

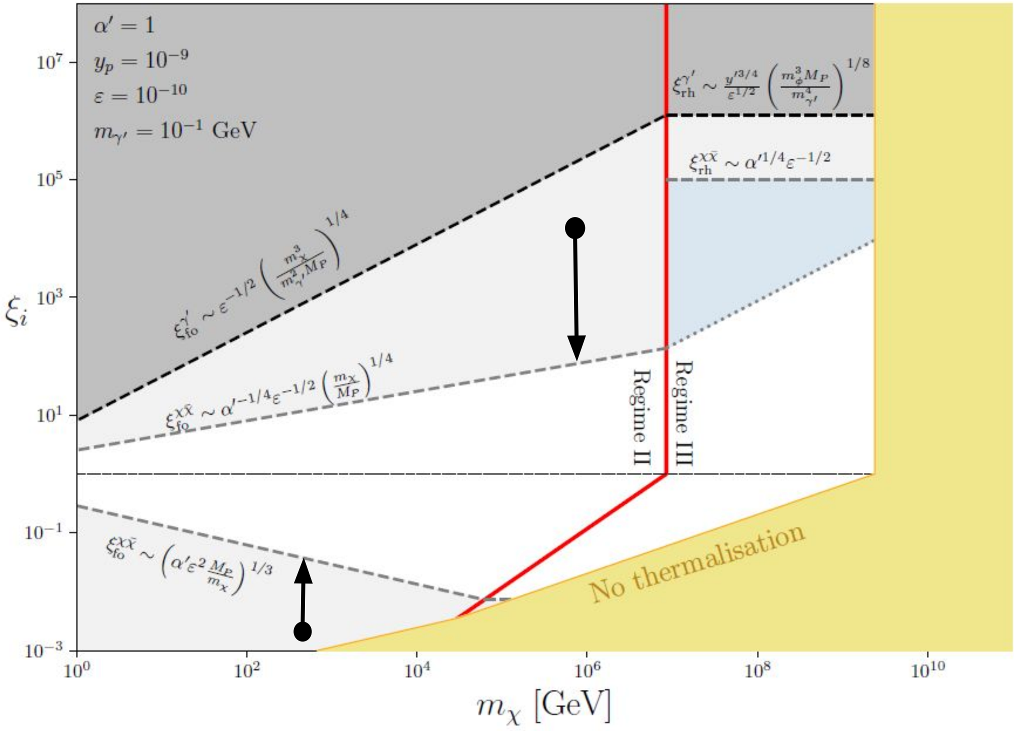


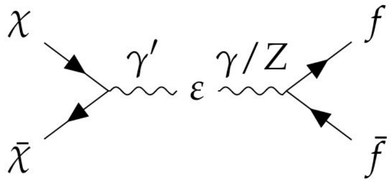
SC, Kimus, Tytgat, **2605.09686**

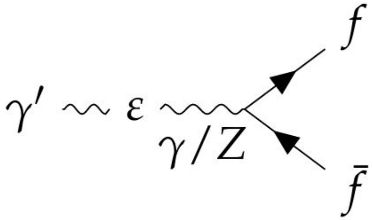
Evolution of the temperature ratio ξ

Effect on ξ stability of **large kinetic mixing at fixed dark photon mass**

$T_{\rm rh}^{(\prime)} \sim 10^7$ GeV

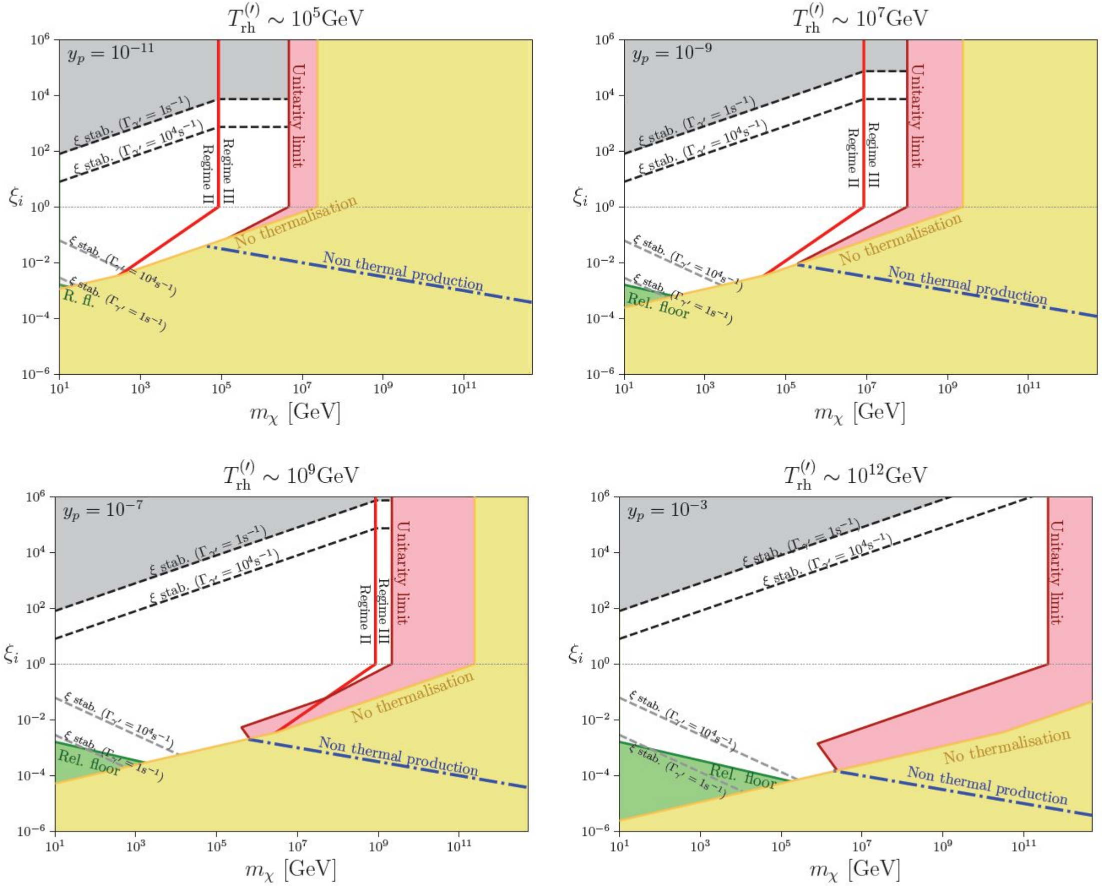






SC, Kimus, Tytgat, **2605.09686**

Thermal Dark Matter domains



SC, Kimus, Tytgat, **2605.09686**